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THE SPECIALISTS' SERIES.

VOLUME II.

GAS ENGINES.

BY

WILLIAM MACGREGOR.

WITH SEVEN PLATES.

LONDON:
WHITTAKER & CO., 2, WHITE HART STREET,
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GEORGE BELL & SONS, YORK STREET, COVENT GARDEN.
1885.

PREFACE.

MOTIVE-POWERS have a division by natural selection into two classes—large and small. The latter might again be divided into manufacturing and domestic. Large powers have been, and are for some considerable period in the future likely to be, provided by steam and water. By large powers are here meant thousands of horse-power.

But, for the hundreds of horse-power required in daily increasing manufactures the gas engine is at present adapted, and has an economy in application rivalling even the steam engine. For the tens and units of horse-power employed in our smaller industries and in domestic requirements the gas engine has become unique.

And it is very strange that an industrial machine having so wide-spread application should have no literature. That this is so is sufficient apology for the issue of this work, however great its sins of omission.

That the work should be exhaustive has not been the aim: rather that it should be typical. In this view an historical machine has, in some instances, been described, instead of the engine, as mechanically more nearly perfect, for the reason that the principle is more clearly shown by the earlier design. Yet in every such instance reference will be found to have been made to the latest patents.

In dealing with the theory of the gas engine all references to the cycles of Carnot and to the engine considered as a theoretical heat engine have been very carefully avoided. For in practice the gas engine has no affinity whatever to these cycles; except such as a straining of the truth to so great an extent as to exclude the effect of the most important practical factors—as the cooling effect of cylinder walls—might obtain. This is very clearly proved by a careful and unbiassed study of the practical cycles of the machine as given by the indicator-diagram; and is involved in the consideration of the superior efficiency of high piston velocities. The superior economy of compression engines and the relatively closely succeeding standard of the free-piston engines are facts that have not yet been satisfactorily correlated by any merely theoretical thermo-dynamic consideration. Hence, in the portion of the work devoted to the theory of the gas engine, the readers attention has been confined to the deductions that have been obtained from experiments made by the best authorities. In addition to these experimental results are those given as confirming the clearest views to be had on the important but little studied subjects of the velocity of propagation of combustion in gaseous mixtures and of the explosion wave.

In conclusion the Author would refer to the table of contents as to the division of the work; and he wishes to point out that perfect independence of position and thought has been sought.

W. M.

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GAS ENGINES.

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Papin describes, as thought out by him, in the proceedings of the Leipsic Academy for 1688, a similar machine provided with regular valves. The labours of these pioneers were not crowned with success, and the gas engine remained in this embryo condition for more than a hundred years.

Towards the end of the last century attempts were made to employ the expansive force of permanent gases in motors. In the year 1791, **John Barber** took out a patent in this country for the production of force through the combustion of hydrocarbons in air. It is shown by his description that he desired to turn into gas, by means of external firing, wood, coal, oil, or other combustible stuff, mixing the product with air in a second vessel, which he calls the exploder. The mixture on its running out of the latter vessel was ignited so that the issuing flash turned a paddle-wheel or fan. He also says it was an object to inject a little water into the exploder in order to strengthen the force of the flash.

In a patent which **Robt. Street** took out in 1794, a piston engine is described, in the cylinder of which coal tar, spirit, or turpentine is rendered gaseous in the first instance, and then ignited by a light, which burns outside the cylinder, and at the proper time may be placed in connection with the gases to be ignited. Through the explosion the piston is thrown up and moves a weight on which the work of the engine depends. The whole is, however, very imperfectly arranged.

To the engines already named is to be added that of **Franzose Lebon.** In an additional patent of 1801 to his earlier patent, on the construction of a furnace for the production of illuminating gas, he describes a machine which could be driven with such gas, and corresponding completely with our present gas motors. For example, by means of two pumps he compresses air and gas, separately into a recipient; here the constituent parts unite, and the mixture is ignited. The combustion products, whilst they are expanding, overflow into a double working cylinder, driving the piston and doing work on both sides. For the ignition, however, the inventor recommends an electric machine, which, like the two pumps, should be driven by the motor itself.

From this time forward the number of new constructions increases. It would lead us too far to detail them all; only the most important will be noticed.

In 1823, **Samuel Brown** specified the arrangement of an atmospheric gas engine. Below the piston in a cylinder, open at the top, and provided with a water-jacket, is the mouth of a gas pipe. If the piston is in its lowest position then the gas issues from the conducting pipe, and is ignited outside the cylinder, at a flame which can strike through an opening into the interior. This opening is closed whilst the piston, by the active force of the fly-wheel, is moved upwards, so that at first a strong flame burns in the cylinder; this expands the air, so that a part of it disappears through valves in the piston. These close so soon as the piston has reached its highest point. As a consequence of cooling with water, the tension behind the piston sinks quickly and the exterior pressure of air drives it down. If, however, the difference of tension is equalised, the piston valves re-open, the combustion products escape, and fresh air can enter. The machine is double-working, as two cylinders are in use, the pistons of which are connected by a working beam. Such a motor has been built in Paris without exhibiting any result.

A direct and certainly double-working machine was patented in 1833, by **Wright**, in which, according to the inventor's expression, a mixture of combustible gas and air was to operate like the steam in a steam engine. This machine shows essential progress compared with previous projects; it stands nearly on a level with modern constructions, has a water-jacket, etc., and flame ignition, and is provided with a centrifugal regulator, which regulates the air and gas supply in proportion to the requirements of the work, so that the total quantity of gas may remain the same, and consequently the condition of the mixture unchanged.

After this a whole series of English and French patents, which merely refer to hydrogen motors, are less worthy of attention. Only one, specified by **Johnson,** in 1841, need be mentioned, as it pointed to the explosive working effect of a mixture of oxygen and hydrogen, as well as to utilising the effect of the vacuum after the combustion.

In contrast to later extravagances, how justly the value of gas engines was recognised is shown in a letter by **Cheverton,** who wrote in 1826 :—" It has been the wish for a long time of the practical mechanic to succeed in the possession of a dynamic engine which is always ready for work without costing too much to drive, and causing no loss of time in preparation. These properties would make it in every case applicable when only a small force is necessary at irregular times ; and the avoidance of manual force is so important that the advantages which society would derive from such a machine would be incalculable, even if the cost should be much greater than with the employment of steam."

Like the numerous constructions of the following two decades, which do not exhibit much that is new, all these machines remain strange to the great circle of technists ; only in 1860, the Frenchman **Lenoir** ceeded in constructing a gas motor which appeared to be useful. The patent dates from the 24th January, 1860, and in a short time afterwards, several such machines, built by the manufacturer **Marinoni**, were at work in Paris.

They caused unusual attention, and justly so; as unscrupulous claims were everywhere put forward as to the inventions. In nearly all technical journals of that year we find the most fabulous reports. That the last hour of the steam engine had struck was without any doubt. This gas engine, independent of all other considerations, worked much more economically than the former. It was given out that whilst the working cost of a 4-horse-power steam engine in Berlin, with 4·5 kilogrammes consumption of coal, per horse-power per hour would represent 6·57 shillings daily, the new motor claimed for the same performance only 3·42 shillings; and similar exaggerations were frequent.

It is just to state, however, that the engine, at the beginning, worked tolerably well, as they were carefully constructed and finished. Through these good properties, many persons were led into giving orders, without any proof of the cost of working; these orders were so numerous that a special company was formed —the Lenoir Company—to undertake the construction. Afterwards, when these motors came into work, and the gas bills appeared, the enthusiasm fell off in an important degree; for whilst the users began on the supposition of a half cubic metre consumption of gas for one horse-power per hour, the brake exhibited, with unerring certainty, that three cubic metres average, at least, were required, and with bad attendance, still more. On that account, the greater part of the machines in active work fell into complete disuse, and the new motor was, in all directions, badly named. It was observed sarcastically that it required "no heater, but only a lubricator."

As is frequently the case, the truth lay half way. The machine was neither so good as it was said to be at the beginning, nor so bad as was stated later on. When it was first brought into practice in the workshop, it was even called very good; it worked, with careful handling, quietly and pretty certainly, only much too dearly. Its good qualities then contributed towards its maintaining its hold in many places, particularly in all where local circumstances, as the irregularity in the requirements of work, excluded the employment of a steam engine, and the question of cost was not taken into account too closely. It was preferred, for a long time, by many on account of its noiseless action—the atmospheric engine appearing about 1867—and it was even exhibited in Vienna, 1873.

Lenoir's priority as inventor of the gas engine was hotly contested by the director of the Parisian gas-works, **Hugon**, and by the Munich watchmaker, **Reithmann.**

The first referred to his patent of the 11th Sept., 1858; the latter, to having worked a gas engine the same year; and in it there was claimed even, that the mixture was compressed before ignition.

If we take from Lenoir the merit of the invention of the gas engine, then this merit applies neither to Hugon nor Reithmann, but perhaps to Barber or Street. Lenoir's merit does not lie in his having been the first to think out the details of a gas engine, but that he made it, and so made it that it worked.

Subsequently to the engine of Lenoir, a later construction of Hugon's was brought out. It was distinguished from Lenoir's principally on two points. The electrical ignition was set aside and replaced by a flame ignition. This idea was not new, as Street and Brown had already employed it; it was, however, good, and has been maintained until this day. Then, instead of cooling the cylinder, as Lenoir and others had done before him, he injected water into it. This was changed into steam, and therefore took up a part of the heat arising from the explosion, and thus protected the moving parts from overheating, as well as operating as expanding steam, driving up the piston. This idea, in recent years, has been taken up; the disadvantages and advantages of such an arrangement will be brought forward later on.

Hugon obtained, by means of his improvements, a reduction in the consumption of gas to about two-and-a-half cubic metres per horse-power. The engine at this period has, however, but little interest.

Kinder and Kinsey stand very near to Lenoir with their engine, which they brought down to consume two cubic metres of gas per horse-power per hour.

The second period in the development of the gas engine begins with the second Parisian International Exhibition, of 1867. Here the firm of Otto and Langen, of Deutz, exhibited their newly-invented atmospheric gas engine. As the name implies, the explosive effect of the gas was in this engine by no means employed direct for the performance of work; it served to throw up the piston of the simple working cylinder, whilst it was out of connection with the shaft of the engine. In order to procure a place for the combustion products, the tension of the latter was caused to sink very suddenly, in consequence of outside cooling, and the vacuum succeeding allowed the piston to fall by its own weight; and now, in connection with the shaft, the stroke of this engine was not so sudden as that of Lenoir's. But it had many drawbacks, and at one time they were relatively very great. It exhibited a series of difficult detailed construction calculated to create a fear as to its durability, and, finally, it made a horrible noise—so much the more unpleasant to the ear as it was quite irregular. Notwithstanding, the engine had a great advantage, which covered all its bad properties: it used very little gas—at the beginning, 1·2 cubic metres; finally, only 0·8 cubic metre per horse-power per hour; a result which hitherto had not been exceeded. It was therefore practically useful for small industries; it could not only compete with the steam engine, but, in many cases, beat it out of the field.

This engine is, however, not without its forerunner. The Italians, **Barsanti and Matteucci**, had some years previously constructed a similar one; yet it is certain that Otto and Langen worked independently. At all events, the Germans had the result to themselves; they pushed forward their machine, whilst that of the Italians came to nothing. The firm ruled the field for ten years, and constructed four thousand of these motors, which, in spite of their shortcomings, were found more and more to be a great boon to small industries, and for social requirements gave the best results of all small motors. The many alterations undertaken by the inventors to make good the deficiencies of their engine, demonstrated their unwearied activity; although they never ultimately succeeded in fully attaining their object.

Through the construction by **Gilles**, of Cologne, at the time of the Paris International Exhibition, of a noiseless atmospheric engine, the supremacy of the Otto and Langen engine appeared to be jeopardised; and it may be considered as the first revolutionary period in the history of our motor, as it caused the inventors to return to the principle of direct working.

In fact, the new motor, named after its inventor, **Otto**, is distinct from its predecessors. Externally this is the case by its very pleasing appearance, quiet, regular action, and harmonious dimensions; and, according to principles, in three points. In the first place, by the compression of the gas mixture before ignition; and, on account of the diminution of the dimensions, by a greater piston velocity for facilitating the change of heat into work; for prolonging the combustion, by modifying the initial temperature, and by better employment of the heat generated in consequence of the cooling of the cylinder.

In fact, the Otto is one of the most pleasing constructions in the domain of engine construction, and a striking example of indomitable skill, as well of deep thought.

As concerns the cost of working, the consumption of gas stands only a little higher than that of the atmospheric engine; the smaller powers use, on an average, 1 cubic metre per horse-power the hour, whilst for the larger constructions the consumption of gas is modified to about $\frac{3}{4}$ cubic metre.

On that account the success of the motor was quite extraordinary and permanent. In four years, over five thousand were circulated.

The above short survey of the material of this publication may justify a historical division of it. In fact, such a division follows closely the three periods: before the second Paris International Exhibition, from the second to the third, and after the third; with the practical divisions corresponding to the epochs of direct working engines without compression; atmospheric engines; and direct working engines with compression.

PART I.

CHAPTER I.

DIRECT WORKING ENGINES WITHOUT COMPRESSION.

Lenoir's Engine.

It is an important question why gas motors, such as Lenoir's, Hugon's, Hicks's, &c., distinguished for their non-recoiling action, worked so uneconomically, and why they were compelled to give way to modern constructions. The essential reason is, probably, that the known older makers did not appreciate the great advantage of compression of the gases before combustion, as well as that the gases in their engines were under atmospheric pressure.

Owing to the want of knowledge of this principle alone the older motors have failed; but imperfectly constructed details might have been improved, and thus prevented complete extinction. This view is best supported by the circumstance that, after the Lenoir motor had scarcely become known, the reason of its low economy was ascribed to deficient compression by **Gustav Schmidt**, who pointed out, prominently, the great use of compression. In his "Theory of the Lenoir Gas Motor," printed in the Journal of the Association of German Engineers in 1861, he says:

"The result would have been much more favourable if a suitable compression pump could have been driven by the engine which would compress the cold air and cold gas to three atmospheres before entering the engine, by which a far greater expansion and advantage of the combustion heat would have been practicable."

Besides the advantage of a better and more economical expenditure of the gas by compression of the mixture before combustion, a gradual tension of the chief organ of the engine also assists this, and as well contributes to the object of a completely non-recoiling action. Machines with sudden development of pressure, consequently causing a recoil affecting the whole mechanism, are naturally excluded from the market.

The way in which pressure is developed by the combustion of a gas mixture in the closed space stands in direct relation with the velocity by which the ignition is transmitted in the mixture. If this velocity is great, the pressure in the space increases rapidly; if the transmission is slow, then the increase of pressure in the space is also slow.

The means towards the attainment of a slow combustion and the gradual development of pressure, resulting therefrom, were given a quarter of a century ago to the makers of gas engines, by the high scientific authority of **Robert Bunsen**, in 1857, in his work, "Gasometric Methods," on the subject of combustion of gases.

Bunsen says in the passage treating of combustible gases in closed vessels:—

"If an explosive gas column is ignited at its upper end, by time the combustion reaches the lower end a considerable heat is lost in the upper end by radiation and convection. If the fulminant gas is weakened with neutral gases near the line of ignition, then is often seen at the place of ignition a ball of fire moving slowly away to the lower end of the gas column. In this case the combustion is already ended in the upper part of the gas column, when it is still going on in the lower. The explosiveness of a fulminating gas is therefore not lessened merely by the admixture of inferior gases because the temperature of combustion is a little less, but for the reason that the velocity of transmission of the combustion is diminished."

And further on, as to the ignition temperature of gases:—

"If an explosive gas is mixed in a greater proportion with an incombustible, the limit is reached where ignition suddenly ceases. This limit is so sharply defined that even the smallest addition of incombustible gas changes the yet really combustible gas into one completely incombustible. Such a gas, changed into incombustible gas, regains its combustibility again when it is prevented from free dilatation when ignited, or when its temperature has become higher."

In fact this simple means of suitably thinning an explosive gas mixture by an indifferent non-participating gas lies at the basis of all non-recoiling motors, from Lenoir's to Otto's.

According to Bunsen, a little more or less of neutral gas is sufficient to make an explosible gas combustible or incombustible, ignitible or not ignitible; therefore the constructors of gas engines make it a principal point, for the object of an easy and certain ignition of the diluted mixture, to form the mixture so far unequally as to bring to the place of ignition a mixture easily ignitible. In this respect the older and newer gas machines do not differ from each other.

The mode of working Lenoir's engine will be presently described. He conducts air and gas in the proportion of 20 to 1 through a number of conduits lying next to each other, into the cylinder. In the suction an equal number of gas and air currents are formed which mix, at first gradually, through movement and diffusion.

The air is more than double the quantity necessary for combustion. It is provided from the atmospheric air, but there is also a considerable dilution which still further increases the quantity by an important combustion residiuum that remains in the conduits and cylinder. In these engines this combustion residuum amounts to about one-third of the charge.

The ignition of the charge in the cylinder takes place at the outflow passages of two particularly short gas and air conduits, therefore at a place when we may certainly assume that no combustion residuum is found, and where, however only in this special conduit, a partial mixture of gas and air has already taken place. In consequence of this an explosive flame is formed on ignition in this conduit, which strikes into the cylinder and the diluted mixture in it is ignited with certainty.

The non-recoiling action of the Lenoir machine was immediately ascribed, after publicity of the mixture of explosible gas with surplus air, to the existence of neutral gases.

In the Journal of the Association of German Engineers, of 1860, it is stated "the heat generated by combustion dilates the steam, carbonic acid, nitrogen and the surplus air that are formed, and thereby drives the piston against the opposite side of the cylinder, whereupon a fresh detonation takes place on the other side of the piston, which ought to be free from any observable recoil in consequence of the great overplus of air."

It is stated also in the "Polytechnisches Central-Blatte" of 1861, in an article "On the Theory of the Lenoir Gas-Engine," by Hirn :—

"The assumption is insufficient that the ignition of the gas takes place immediately, and that therefore the tension in the cylinder is greatest at the beginning of the piston stroke, because the gas mixture, not only requires a certain time in order to become ignited, but there must be upon the beginning of the piston stroke a certain interval ere the ignition enters. Because of this the maximum of tension cannot be obtained in practice."

From this it is clear that as early as in the year 1861, the existence of neutral gas in the cylinder of the Lenoir engine was known, that the non-recoiling action of the engine because of this neutral gas was explained; and the desirable point of ignition was also pointed out in diagrams, that is to say, the gradual increase of pressure in the combustion was indicated.

Lenoir's engine, as constructed by Marinoni, in Paris, had externally much resemblance to a horizontal steam-engine of old construction, of which it is manifestly an imitation. In Fig. 1, it is represented as double working. In the cylinder A, which is provided with water jacket and double walled cover for cooling, works the piston B, the rod of which, C, carries the crosshead D, and this is connected with the fork E, so as to carry the movement to the crank-shaft F. Gas and air are admitted by the inlet slide G; the exhaust of the combustible product is by the outlet slide H; both are moved by the eccentrics J and K. Whilst the outlet slide is provided with only two slots, and these coincide at the right time with the outlet conduits of the cylinder, the inlet slide of the cylinder is not so simply contrived. Fig. 2 shows one view of it. It is to be observed that its ends are grooved up; the gas enters through the holes *bb*, scarcely 2 mm. in diameter, when these are coincident with the gas failed of high efficiency more from inaccurate construction than from erroneous theory. In this subject, as in many others, it is remarkable to see how closely to later and successful practice, the pioneers had arrived, and how they were swerved from their course by trifles of mechanical construction that were the sole cause of want of practical success.

The patent specification (No. 335, of 1860) states that the "invention consists in the application and use of an inflammable gas mixed with a proper proportion of atmospheric air and ignited inside a cylinder by the aid of electricity, the expansion thereby produced acting upon the piston and imparting motion thereto, which motion may be transmitted in any convenient and well-known manner to a driving shaft."

In carrying out this invention it is proposed, in the patent, to apply two slide valves to the cylinder on opposite sides, or to use a disc valve. These slides are not contained in boxes as in the ordinary steam valve, but are held against the valve faces of the cylinder by springs or screws. Suitable means are employed for admitting atmospheric air into the cylinder. Along with this air there is also admitted, by means of a pipe employed for that purpose, a supply of ordinary lighting or other inflammable gas or vapour. Inside the cylinder are fitted, either at the middle or at both ends, one or more pairs of insulated platinum or other wires in connection with a battery, and so disposed that an electric spark will be produced which will instantly ignite the mixture of air and gas contained in the cylinder on one side of the piston, and by the expansion so produced force the piston to the opposite end of the cylinder. The supply of gas is regulated by a suitable stop-cock and governor.

Fig. 3 represents a side elevation; Fig. 4 is a corresponding plan and partial horizontal section; and Fig. 5 is a transverse vertical section of the working cylinder. The working cylinder A, cast with a jacket, is provided with two valve faces, upon which work the two slide valves T and T^1 which open alternately, and at the proper times, the ports a, a^1 and a^2 for conducting the mixture of air and gas to each side of the piston as well as the ports b, b^1 and b^2 for the emission of the products of combustion. The valve T, which regulates the inlet of the air and gas into the cylinder, is provided with an orifice t, which communicates with one or other of the two openings o, o^1, made in the plate P. This plate carries the two cocks r, r^1, which admit the gas. The introduction of atmospheric air takes place through the port a, which is in communication with the open nozzle b^{II}, surmounted by a cap b^{III}, as shown in Fig. 5. The slides are held against the valve faces and work outside, by guide rods, which slide in the bearings C, C, the usual steam-engine valve chest being dispensed with. These bearings are so arranged as to enable the slides to be set up more or less tightly against the valve faces by means of pressing or adjusting screws, as shown in Fig. 4. The cap b^{III} acts as a species of gasometer, that is to say, it retains the gas which would tend to escape, and which can then enter or be drawn into the cylinder at the next stroke of the piston. The movement of the piston *p*, is transmitted to the main crank-shaft B by the aid of the connecting rod C^{I} which is secured to the crank of the main shaft. The two eccentrics D and D^{I} actuate the slide valves T and T^{I}, and a small pulley, E, imparts motion by means of a strap to the governor or regulator of the machine. The cylinder is provided at each end or has fitted upon its two covers the igniters G and G^{I}, in communication with an electric distributor H, carried by the main driving shaft, and is itself in connection with a Rhumkorff coil, which is in communication with any convenient battery or generator of electricity. In starting the engine the piston *p* is first caused to travel a certain distance along the cylinder, producing a vacuum behind it and allowing the air and gas to enter the void space through the ports *a* and a^{I} respectively, but as the slide T opens the port *a* before the passage *t* comes into communication with one or other of the gas inlet orifices, *o*, o^{I}, it follows that a supply of air will have already entered the cylinder. The slide T then opening one of the orifices, *o*, o^{I}, in the plate P, the gas and air both enter the cylinder, but without becoming entirely mixed together, and will exist in the space behind the piston *in distinct strata.* The slide T, now closes the port leading to that end of the cylinder, and, the igniter G suddenly producing an electric spark, the gas explodes and heats the air and its combinations, which expand considerably, and the pressure produced operates upon the piston so as to force it to the opposite end of the cylinder, the residuum of the combustion or its products escaping by the exhaust slide valve T^1 and passage *b*. The fly-wheel assists the piston in its course towards the end of the cylinder and, the slides T and T^1 changing their positions, the air and gas are introduced to the other side of the piston just at the moment that the second igniter G^1 produces a spark, which ignites the gas and causes the piston to return to the opposite end of the cylinder, thus completing a double stroke. According to the patent, the object of introducing a supply of air into the cylinder before the gas is allowed to enter is to neutralise the effect of the carbonic acid gas formed by the combustion of the first portion of the inflammable gas; as the carbonic acid gas without being thus neutralised might prevent the ignition of the remainder of the inflammable gas. As the machine in working attains a considerable temperature, it is proposed to introduce into the jacket a suitable supply of cold water, regulated by the cock *l*, and which water becomes heated or converted into steam and flows off through the pipe l^1, to any place where it can be stored or used. The apparatus termed the director of the electric current (a sectional detail of which is shown on an enlarged scale, Fig. 6) consists of a species of collar or ring of hard indiarubber, gutta percha, or other good non-conductor, L, in the periphery of which are inlaid the metal segments M, M^1. The segment M^1 rotates in constant communication with the conducting wire N, leading from the coil, and the segments M, M^1, with each one of the directing wires *g* and g^1, these wires being respectively connected with the igniters, G and G^1. The short metal rods *m*, m^1, unite the metallic contact segments of the director with that of the conducting wire N. As the cylinder conducts one of the poles, the operation of the director will be readily understood. It is mentioned in the patent that if found desirable, liquid or solid hydrocarbons may be employed in this engine for heating and expanding the air and its combinations; in which case the substances from which the inflammable gases or vapours are to be obtained are placed in a small boiler and are heated by means of a serpentine or coil placed in the bottom of the boiler and in direct communication with the escape pipe of the engine. The boiler is first heated and, so soon as the hydrocarbon is converted into vapour or gas, it is placed in communication with the working cylinder. The vapour so produced is ignited in exactly the same manner as the inflammable gas before mentioned, and similar effects will follow. And it is also claimed that it is obvious that this invention may be applied to coupled engines of two or more cylinders, suitable for steamboats and locomotive or traction engines.

The claims of this pioneer patent are so very definite that we may find space to reproduce them here; they are: (First). The general construction and arrangement of machinery or apparatus for obtaining motive power by the aid of inflammable gas or vapour in conjunction with atmospheric air as hereinbefore described. (Second). The employment of electricity for the purpose of igniting gas or inflammable vapour when used for the obtainment of motive power as hereinbefore described. (Third). The application and use to and in the heating of air in the cylinders of motive power engines of solid or liquid hydrocarbons converted into vapour as hereinbefore described. (Fourth). The application and use of electro-igniters placed in the cylinder of a motive power engine for the purpose hereinbefore described. (Fifth). The application and use of a director of the electrical current, for the purpose of bringing a spark to bear at the proper time and place upon the gas or vapour to be ignited in a motive power engine as hereinbefore described.

This earlier motor of Lenoir is very remarkable as being a double action motor, that is, pressure or motion was imparted to both sides of the piston alternately. In the Lenoir engine first described, which may be said to date from 1877 (French Patent, No. 117,390), the action is much more simple.

Lenoir's Engine, 1883.

But neither of these engines must be confounded with that of Lenoir, patented in this country in 1883 (No. 5,315), which is essentially a compression engine, with explosion of the gaseous fuel under constant volume.

In this improved engine, of which, from its recent introduction, there has been but small experience, a regenerator or reheater is employed, which is placed in a prolongation of the explosion chamber at the cylinder of the motor. Exhaust is made through a valve M as controlled by the rod and crank $n\ n^1$, Fig. 7. This valve is placed at the base of the heater. The mixture is drawn into the regenerator, where it is compressed before being exploded. A screw-cock, inserted in the cylinder about the middle of the stroke of the piston, allows of varying as desired the compression of the mixture.

With the slide-valve of the new Lenoir engine, as the same letters correspond to similar parts in the Otto engine, to be presently described, it is unnecessary here to say more than to refer to the Fig. 8. *g* controls the admission of the gas, *a* that of the air, *j* gives entrance to the mixing chambers, and bb^1 access to the burners (the new engine is not electrically lighted) and ll^1 allows of the passage of the ignition flame, which is, as in the Otto engine, caused to impinge upon the richest part of the mixture. The lighting port carries a small projection to push the flame towards *l*.

Hugon's Engine, 1865.—The working of Hugon's engine is as follows: When the piston, Fig. 9, is lowered, it draws in a detonating mixture furnished by the pump or by the rubber bag M, across the mixing chamber, U, at the same time that it expels from the lower part of the cylinder the products of the preceding explosion. When the piston arrives at about four-tenths of its course, the principal slide, K, descends and closes the communications, *a*, of the orifice of admission, *a*, with the mixing tube, U. At the same time the igniting flame, projected into *a*, causes the explosion.

Similar processes occur inversely on the rising of the piston. The engine is further provided with a pump, S, which injects at each stroke a small quantity of water, at the instant of explosion, for the purpose of reducing its violence and to cool the cylinder. The distribution of the gas is effected by two slides, one, K, serving for admission, for the exhaust and for igniting; the other, L, serving to close the admission orifice and to terminate the drawing in of the mixture into the tube U.

The principles of good working do not seem to have been so well understood in designing the Hugon engine as with its predecessor, although at the time when this motor was brought into public notice, there were, concerning it, some very great expectations.

This engine is distinguished from Lenoir's in two principal points—by the injection of water into the cylinder, and by flame-ignition. The injection of water was intended to take up a part of the heat suddenly created by the explosion, so that it might, by evaporation, co-operate in the expansion, and, at the same time, effect a diminution in the expenditure of oil for lubrication.

When the engine was first brought into publicity, it showed proof of long-protracted studies by Hugon. He intended, at first, to bring out an atmospheric engine. He desired to obtain a higher pressure by the explosion of the gas mixture, producing a vacuum by the subsequent cooling of the combustion products, and to employ this for the movement of the piston. He had laboured long at such engines; they, however, never attained any importance. His direct working engine, however, has given some actual results; but it is several years later than that of Lenoir.

It is, like the latter, double working, but arranged vertically.

In order to make the feed independent of the changing pressure in the gas conductor, the air and gas mixture is prepared in a fixed rubber bellows. A second smaller bellows serves to fill the reservoir, out of which the four ignition flames are fed. It can be moved by hand in order to ignite the flame before putting the motor into action; and this starting is effected with all small motors by turning the fly-wheel.

The machine was a step in advance of Lenoir's; it worked as quietly, and, on account of the flame ignition, more certainly, besides being more economical in oil and gas consumption.

Some experiments have been made with it; for example, a machine of three hundred and thirty and three hundred and twenty mm. stroke worked with 0·55 metres piston velocity. The mechanical working efficiency was 0·58, the proportion of the mixture 1 : 13·5, the maximum tension 3·8 atmospheres, the gases escaped at 190°.

Hugon ignites the explosive mixture at the entrance of the conduit, which conducts it to the cylinder, consequently at a place where it is absolutely free from steam and combustion residuum and therefore easily ignitible.

Bischopp's Engines.

For small powers Bischopp's engine has been that most extensively employed, and the simplicity of its mechanism is for such powers greatly to its advantage. It is, however, questionable whether the arrangement of parts is applicable to higher powers than one horse-power with very great success. It is essentially a non-compression engine. The types before the public are those constructed by Bischopp, in 1872 and in 1874, and in 1882, and those modified by **Carl Max Sombart.** In the 1872 and other types, as in Lenoir's engine, a locally separated introduction of gas and air into the cylinder takes place, but in such a way that there are formed below the piston, layers of gas and air, each singly approaching the direction of the axis of the cylinder, has an equal combination, whilst in the normal direction the single layers are essentially separated from one another.

The layer which lies over the gas valves and the air valve quite close to it, contains mixture easily ignitible, whilst the layers over the air valves farthest from the gas valves, consist of almost pure air, and between the first and these latter, of transition mixtures.

The ignition takes place in the layer of the easily ignitible mixture over the gas valves and is here conducted with the greatest certainty.

Whilst the charge in the cylinder of Lenoir's engine is an almost equal mixture, owing to the method of entrance of the gas, it occurs in Hugon's engine in a seriously unequal combination, whilst in Bischopp's motor, on account of the peculiar locally separated introduction of air and gas, it consists of a stratiform disposition of explosive and a neutral gas.

This effort to obtain a stratified arrangement of the charge in the cylinder is met with in many later gas engines; it appears first, however, most strikingly in that of Bischopp, of 1874.

In de Bischopp's English patent, 1910 (1874), which only obtained provisional protection, but the ideas of which were carried out in patent No. 4342, of 1875, we must recognise this invention from the description, especially with reference to the foregoing, to be clear and distinct.

The description of the patent begins as follows:

"This invention relates to the production of a motive power by the combined action of an explosive compound and heated air upon the piston of a reciprocating or other engine."

The inventor describes the construction further and says: "The explosive gases must be led into a confined space under the piston; and it is sufficient for the object of localising the gases, connected with the [illegible] heating of the air, [illegible] the explosive gases, [illegible] arranging themselves according to their specific weight, are led under the piston [illegible] cylinder. As an advantage it may be noted that the noise of the explosion is very much lessened by this arrangement."

In describing the process of working, it is clearly expressed that an elastic cushion is formed to take up the recoil and diminish the noise.

As the earlier forms of this motor have been discarded it is scarcely necessary to describe them here, for a sufficiently clear idea of the arrangement and method of working can be obtained from the improved form as introduced by Carl Max Schumann, of Buss, Sombart & Co., of Magdeburg. These improvements are carried out in three sizes of motors, giving [illegible], or twenty-five kilogrammetres, or [illegible] horse-power respectively. Some of these improvements are very practical, and consist in the separation of the base-plate from the distributor K (Fig. 11), to avoid heating of the distributor and to facilitate repairs; in replacing the two weak arms carrying the shaft, in the older forms, by a single casting; in protecting the regulation-valve against injury by flame, by a disc of perforated sheet iron; and in regulating the admission of gas by a special apparatus.

In the single working cylinder, A, the piston B operates; its rod carries the cross-head C, which is introduced into a hollow column and constructed with the upper cylinder lid D, in one piece. This column is opened up longwise; through the opening the bent lever E enters, which operates the crank F. The shaft G (Fig. 11) forged with the latter, is held in a casting, H, on one side of the cylinder cover, the eccentric, J, fly-wheel and pulley being also carried on the shaft. Such a restricted crank action is not to be commended; the circumstance that the crank action for the up-movement of the piston is greater than that for its lower, does not improve the regularity of the movement. But it must be noted that those circumstances which make the construction of large machines worthless are, in very small machines, of less importance.

The gas pipe *a* is provided with a clack-valve, this consists of a rubber plate, which covers a considerable number of fine holes, arranged in the form of a ring, of about three mm. diameter. In a similar manner the air passes through the clack-valve *c*. Gas and air mix in the regulating cylinder or distributor K, between the pistons of which, *d* and *e*, they enter, when the under one does not close up the inlet conduit into the cylinder through the conduit. Of the two pistons *d* and *e*, the upper one only serves for the closing of the regulating cylinder; the under one operates, besides, the discharge of the combustion products, which, by means of the opening *g* can enter through it into the discharge pipe *h*.

The engine works in such a way that the piston is drawn upwards out of its inert point by the momentum of the fly-wheel, and thereby draws in the mixture. After it has passed somewhat more than a third part of its up-stroke, the ignition follows through the hole *i*, in the cylinder wall, Fig. 13.

So soon as the ignition has taken place, the strongly compressed combustible products drive the piston to the end of its lift; this short space of time is the working period of the engine; it receives during that time the necessary impetus to drive out the residuum, and with fresh action to be able to draw new mixture in again. The eccentric J must, therefore, be so set that the edge of the regulating piston *e* passes in descending the upper edge of the conduit, when the driving piston stands at the lower point of inertia. In this position the engine is shown in the figures. As already mentioned, the ignition takes place through an aperture, *i*, in the wall of the cylinder. As shown in Fig. 13, this aperture is provided with a little clack of steel plate which is opened by the external pressure when the aspiration piston has passed it. A gas flame, *k*, burns before the aperture *i* below the flue *l*; the burner is constructed with an igniting flame *m*, because the gas flame *k* is usually extinguished at almost every lift. Bischopp was compelled, on that account, to bring in a second flame below, the only object of which was to relight the upper flame every time it went out. Another advantage is derived from this burner: the flame of the usual arrangement is not sufficiently strong to effect the ignition when the motor is cold. On that account, the older engine of Bischopp, before it could be got into work, required some minutes for heating it, and for that object a separate flame was arranged under the cylinder.

This uncomfortable method is in the later engines removed, and the motor is always ready for work. It may be observed, as shown in the drawing (Fig.12), that for the cooling by water, a number of ribs are arranged round the cylinder, providing for the carrying away of heat by radiation. The gas issues from the gas main, through a rubber pipe into the foot duct, from this a rubber pipe runs off for the ignition flame, then into a rubber bag and through the tap into the engine. The rubber bag serves as accumulator and regulator for the gas main. It should accompany every gas engine; should it fail, then every stroke of the engine is observed in flickering of the gas flames also fed upon the same main.

C. H. Andrew has improved on the Bischopp engine by adding an automatic admission for the gas and for the air, and the mixture is drawn in by a separate piston, which arrangement allows of the slide valve piston being reduced in size.

Haigh and Nuttall, besides improving the valves that admit both gas and air, replace the clack-valve in the ignition orifice by a ball or bullet.

If a strict classification of the various gas engines were possible, there would have to be many divisions and subdivisions; and a subdivision of the class of those engines acting without compression would be in the so-called atmospheric engines of which Barsanti and Matteucci's is the type.

ATMOSPHERIC ENGINES.

Barsanti and Matteucci brought forward in their French patent of 20 February, 1858, two vertical constructions in which the piston is out of connection with the shaft, during the up-stroke, but during the descent is in connection with it, and communicates an impulse to the fly-wheel. In the first construction we have two working cylinders upon the usual main shaft, as in Fig. 14. In the cylinder A the principal piston, B, moves, the rod of which is serrated, or racked, and catches into the wheel C, which runs loose upon the main shaft. C carries the pawl E, and is pressed by a spring into the teeth of the ratchet wheel F, which is keyed upon D. If the principal piston rise, then the wheel is turned to the left; if it fall, then the rotation is to the right, and takes the shaft with it.

The unequal action through such irregular movement of the shaft is equalised by the employment of two alternately working cylinders and the fly-wheel Below the principal piston there is a second, the counter piston G, whose rod goes through the front of the cylinder and carries the traverse H; this is fastened by two lever bars, which hang to the pins of two crank discs, set upon the adjoining shafts J; these obtain their movement from the principal shaft through the wheels K, which revolve more slowly than the shaft. The counter piston, therefore, effects a regular up and down movement; consequently, if the principal piston stands in the lowest position, and the counter piston in its highest, then in the first place the latter goes down when atmospheric air enters between the pistons, at the appropriate position of the slide valve L, through the conduits *a*, *b*, and *c*. After a certain time the arm upon the piston strikes down the end piece of the slide-rod and draws the slide down. Now the air conduit *a* is closed, and the slide communicates with the conduit *d*, conducting the gas, so that now through the connection *d*, *b*, *c*, gas is drawn in between the pistons, until the upper edge of *b* has passed the under edge of *d*. At this moment the mixture drawn in is ignited by an electric spark; the head piston flying upwards free, the counter piston going farther down, whilst it discharges through the foot valves what it finds below it; then it restores the connection between the spaces, above and below it, through the conduits *e* and *f*. In consequence of the foot-valves opening from too much inner pressure, this communication may first occur when the explosive tension has fallen under one atmosphere, through the rising of the head piston. As soon as the head piston is in equipoise it turns and goes down; the counter piston, however, begins its forced ascent quickly, and 't operates the air pressure upon the head piston until the tension in the machine has again attained one atmosphere; then the head piston, by its own force and weight, drives out the combustible product through the foot valves: whilst the counter valve ascends until the first position is again reached. From this description of the action of the engine, it follows necessarily that the movement of the adjoining shaft must be slower than that of the main shaft, so that the descending head piston does not arrive later at its lower position than when the counter piston has reached its upper position: if it arrives too early that does not matter.

The second construction of the patent in question may be seen from Fig. 15. The cylinder here is provided with only one piston, the rod of which is toothed and operates upon the toothed wheel C, which runs loosely upon the main shaft D, and carries the pawl E; this takes with it, in the descent of the piston, the ratchet-wheel F, and the shaft with it, but is free in the up-stroke. If we consider that the piston is arrested in the descent, it must remain standing, for instance, if the tension of the combustion products below it have placed it in equipoise. In order, therefore, that the latter may be driven out, it is necessary to press down the piston, which takes place through the two noses *a* of the stop wheel operating upon the two cams *b* of the toothed rod. When these have brought it down to its lowest position, then the noses *c* of the adjoining shaft G lift it again, and the latter operates upon the cams *d*, in order that fresh explosive mixture may be drawn in; and this is introduced through a slide valve placed at the side. The latter has two positions of rest, its conduits correspond with those of the valve-face when inflow takes place; if this does not occur, then the engine remains closed. The movement of the slide is retrograde, and is effected from D and G; the noses *c* and *a* work upon the catches *g* and *h* of the slide bar, so that it goes down with the piston, and consequently the inflow may begin immediately: after the piston has reached the lower part, it is ended. As soon as the piston is lifted up, the cutting off of the inflow immediately follows.

Langen and Otto's Engine.

The first engine of Langen and Otto was made known through the Paris International Exhibition in 1867. The pattern exhibited was half horse-power, and caused unusual attention from its peculiar construction and noisy action.

Opinion, however, of the new motor would have been unfavourable if the economy of consumption of gas, in comparison with the engines of Lenoir and Hugon, had not been apparent. According to the publications of that time, the judges were forced to praise the engine for its economy, yet to blame it for its construction.

If the arrangements of Barsanti and Matteucci had been more generally known, the new invention would scarcely have excited so much wonder, because in its disposition of the free up-stroke of the piston, and the gearing of shaft with it in the down-stroke, the Italians show exactly similar designs. What is interesting in Langen and Otto's engine is the gearing arrangement; this and the flame ignition constitute the essential distinction and progress.

The engine is vertical. In the vertical upper open cylinder the piston moves, the progress of which above is limited by a rubber buffer. The toothed piston rod, carrying a traverse above, slides between two pillars standing on the top cover of the cylinder. The piston conveys its motion to a toothed wheel, and this takes the head shaft with it in the descent of the piston by means of a friction coupling; on the ascent of the first, however, it slips loose upon it. An auxiliary shaft, which is driven by similar toothed wheels, provides for the guiding of the distributing slide.

The engine works in the following manner. From the lower dead point position the piston, in the first place, is lifted by the stored power of the fly-wheel, and the slide is so placed as to allow the explosive mixture to enter. Immediately after the inflow is completed, the ignition follows; the piston flies upwards, and the toothed wheel turns round to the right, whilst the shaft, not in gear, turns to the left. The tension below the piston now sinks, in consequence of the explosion, and, at the same time, cooling takes place, so that when the piston comes to rest, after the employment of the active force imparted at the beginning onsiderably below the exterior air pressure. n now changes its movement, and goes down quence of the exterior air pressure and its own whilst it actuates the shaft. The tension below adually increases. The effective force upon the is, therefore, a decreasing one, so that its y by this time is less than the peripheric velo- of the shaft. The piston now drives out the ossible product, whilst it sinks farther down by its weight. The piston movement, consequently, sists of four periods. In the initial period it con- mes a part of the active force of the driving shaft; ring the upstroke it is independent; in the first part the downward action it increases the active force of he shaft; in the latter part it is again free from it. The useful work is, therefore, equal to the difference due to the operations in the third and first periods.

In order that this manner of working, as described, may be attained in full, three mechanisms are neces- sary: friction coupling, the arrangement for lifting the piston and the distributing slide valves.

The friction coupling it is unnecessary to describe here.

In order to be enabled to understand the valv motion the slide movement must be first explained The slide which glides between the valve-face a slide cover and is tightened whilst the latter is press by four spiral springs, arranged beneath by tightening screws, is to provide for inlet, outlet and the ignition. It usually stands, as Fig. 16 shows it, with the outlet conduit open. This goes through the valve-face and slide cover, and is closed by the flap valve, *g*, which rises as soon as the tension in the cylinder is greater than the outside pressure of air. The piston is thereby put into position during the last part of the downward action to drive out the combustible product. The gas flows through the bore, *h*, the air through bore *i*, into the slide cavity *k*. Whilst, therefore, the slide goes back from the position, Fig. 16, into the position, Fig. 17, its lower dead point position, and from this into the first, the detonating mixture can enter through the conduit *l* below the piston.

The slide should also provide for the ignition. The cavity, *m*, is filled with explosive mixture when it is near its lowest dead point position; the gas enters through the bore, *n*, of the slide, the air through the trough, *o*, into this; the mixture is ignited by the gas flame in the slide cover. If the slide now goes upwards, then the chamber, *m*, is immediately closed; in it burns the so-called intermediate flame. Now it passes the position, Fig. 16, and enters into that of Fig. 18; the mediating flame strikes into the cylinder, and ignites the detonating gases there.

Thereafter the slide passes through its upper dead point into the first position, and remains there until the beginning of a new cycle. It is, however, to be observed that it must not come too soon into this position; the tension below the piston must be sunk below it sinks considerably below the exterior air pressure. The piston now changes its movement, and goes down in consequence of the exterior air pressure and its own weight, whilst it actuates the shaft. The tension below then gradually increases. The effective force upon the piston is, therefore, a decreasing one, so that its velocity by this time is less than the peripheric velocity of the shaft. The piston now drives out the combustible product, whilst it sinks farther down by its own weight. The piston movement, consequently, consists of four periods. In the initial period it consumes a part of the active force of the driving shaft; during the up-stroke it is independent; in the first part of the downward action it increases the active force of the shaft; in the latter part it is again free from it. The useful work is, therefore, equal to the difference due to the operations in the third and first periods.

In order that this manner of working, as described, may be attained in full, three mechanisms are necessary: friction coupling, the arrangement for lifting the piston, and the distributing slide valves.

The friction coupling it is unnecessary to describe here.

In order to be enabled to understand the valve motion, the slide movement must be first ex [illegible]
The slide, which glides between the [illegible]
slide cover, and is tightened wh [illegible]
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Thereafter the slide passes through its upper dead point into the first position, and remains there until the beginning of a new cycle. It is, however, to be observed that it must not come too soon into this position; the tension below the piston must be sunk below the outside air pressure; otherwise a partial escape of the expanding explosive gases would take place through the cover *g*.

To carry out the slide movement, there are two eccentrics upon the shaft to regulate the engine. It is required either to vary the gas tap of the feed pipe by hand, or to make it self-acting by a centrifugal regulator; the mixture is thus rendered poorer in gas according to the requirements, and the piston is not forced so high as with full requirements, whilst the number of the piston strokes remains the same. Such an arrangement, however, would not be good, because the engine works best with a certain height of piston movement; and also with greater poverty of gas, ignition is easily prevented, and then unconsumed gas passes through the engine. On this account it is better to put a tap into the discharge pipe. If we close this, more or less, by hand, or automatically by a centrifugal regulator, there is caused a slower outflow of the combustible gases, also a slower falling of the piston, already independent of the shaft, and therewith a diminution in the number of the piston strokes, whose height now remains the same in consequence of the explosive mixture being always equally compressed.

The temperature of the exhaust gases changes with the number of the piston strokes; it was found for forty-five, thirty-seven, twenty-eight, twenty strokes per minute respectively, as 220°, 202°, 180°, 140°; the cooling was effected from a reservoir which contained only 70·1 cubic feet of water, the temperature of which was 15° at the beginning; after ten hours, however, it entered the engine at 67° and left it at 83°.

The engine described was improved in many respects by the inventors in the course of years; but what has been shown indicates the first principles of gas-engine construction; it would lead us too far to give here a detailed historical development.

Gilles' Engine.

The older machine had especially one bad feature. Its velocity could not exceed thirty-five piston-strokes in the minute, without causing danger to the moving parts, and the noise to be intolerable.

The motor, by Gilles, of Cologne, arose out of the endeavour to overcome the objectionable noise of the Langen-Otto Engine. It is especially distinguished from this by the arrangement of two pistons instead of one. The lower working piston is connected with the shaft by a crank and rod, the upper piston serves only for reducing the blow when it is driven up by the explosion, and so creates for the explosive gases room for expansion.

In Fig. 22, A is the working piston, B the flying piston, and C the vertical cylinder closed above. If the former is at its upper dead point, it then moves downwards in consequence of the stored force of the fly-wheel. The flying piston, as the air valve *a* is placed, causes air to enter in the upper part of the cylinder, until the traverse *b* rests upon stops on the cylinder cover.

In the meantime the working piston has gone down so far that the inlet canal for gas and air, *d*, gets into connection with the space between both pistons; then begins the suction, and gas and air enter through the openings of the covering of the distributing valve chest and through the cavity *g* of the distributing slide valve *i*. So soon as the filling is drawn in, the slide *i*, governed by a cog-wheel *h*, begins its upward movement. It cuts off the entrance first and then promotes the ignition, whilst it cuts off the point of the burning flame in the cavity *k* of the cover of the valve chest in the conduit *l*, and throws it into the entrance conduit *d*. At the same time the air slide closes up. The ignition therefore follows and the working piston receives an impulse, whilst the flying piston is thrown up at the same time. The air found above it escapes through the holes *m m*, which are closed by the rubber band *n*; the air, therefore, can escape through them but not re-enter. As soon as the flying piston has passed these holes, it begins to come to rest whilst it compresses the air above it. Now it is caught up by a particular arrangement and held fast in its highest position. In the meantime the working piston passes through its lower dead point; and, a vacuum having been formed between the pistons through the cooling of the cylinder walls, it is driven up by the pressure of external air. Shortly before it reaches its upper dead point, after it has passed the inlet conduit, the slide *a* is again reversed, so that air may enter above the flying piston; at the same time the latter is set free and now goes down, driving out the combustion products through a self-acting valve (not shown) about midway of the cylinder. The air slide has, therefore, only to prevent air entering between the pistons when the flying piston is quite above. The catch arrangement is thus managed: The brake-checks *p p* are pressed against the bar of the flying piston by the levers *q q*, upon which spiral springs *r r* press. This is caused to happen at the right time through the excentric *s*, which moves the lever *t*, and by it holds up and so relieves the brake during the time when the flying piston is impelled upwards.

It cannot be denied that the action of this engine is ingenious, and the construction in general suitable to the purpose; but the catch arrangement remained always a weak point and interfered with the success of the engine as against that of the Langen and Otto.

R. Hallewell patented, in 1875, No. 2826, an engine founded on the same principal as the Otto-Langen atmospheric engine, which utilises, but indirectly, the pressure of the atmosphere. The explosion of the mixture of gas and air is effected in a vertical cylinder, terminated at the head by a large clapet. The explosion raises the piston when free, and the return stroke determines a vacuum in the cylinder. The mechanism of actuating the double-stroke piston-slide differs from that of the engine described.

The distribution of the supply of gas and air is regulated in this engine by a revolving slide-valve.

Turner patented in England, in 1879, No. 1270, a small gas motor, in which the slide is completely surrounded with water. The valves are formed of vulcanite bullets or balls, this material being specifically and relatively very light. A trial of one of these motors of one-third horse-power, making one hundred and eighty revolutions a minute, and working with a mixture of one part of gas to seven of air by volume, gave a consumption of 1·13 cubic metres, or 3·30 cubic metres per indicated horse-power.

For motors of larger size, above two horse-power, Turner adds to the motor-cylinder a pump, which slightly compresses the gas into the cylinder and completely sweeps out at each revolution the products of combustion and explosion, the explosion occurring when the pump-piston is at the bottom of its stroke. The same inventor also proposes a method of gas distribution by means of two slides. This method of distribution, we cannot, in our limited space, do more than call attention to; it has not been found to have very great advantages.

The motor of **Ravel** (French patent, No. 127,583, of 1878,) has an oscillating cylinder, which admits of the piston acting directly on the motor-crank. The move- of the slide is independent of that of the cylinder.

Robson's motor (English patent, No. 4050, of 1881) is similar to that of Langen and Otto in principle, but differs in points that it is beyond the scope of this book to give in detail.

In Ord's Engine (English patent, 3275, of 1881) the aim was to render the lighting more certain and to allow of a high speed. Two pumps are employed, one for the gas and the other for the air, to impel these into a lighting chamber in the slide of the distributor.

In Benier and Lamart's motor, distribution and lighting is effected by a single slide. The movement of the piston is horizontal, as will be seen from Figs. 23 and 24. The slide is moved by a cam, G, and is returned by a spiral spring. Up to the middle of its stroke the piston draws the detonating mixture by O N *n*. The igniting flame M M^{I}, fed with gas by M and *a*, and re-ignited by the permanent burner M^{II}, enters by N to give the explosion. At the return stroke exhaust is made by N S. These motors, intended for one-sixth to one-half horse-power, are very simple and compact. The reader is referred to the patent specification No. 2074, of 1881, for details.

S. Atkinson's engine of this type, for which patents No. 4086, of 1881, and No. 4378, of 1882, were taken out in this country, has no salient specialty; but other types of gas engines, by the same inventor, that have met with considerable development, we shall describe under the proper classification.

Jacob Schweizer's "Revolver Motor," patent No. 4363, of 1883, includes a new idea, namely, to ignite the mixture at the commencement of the stroke of the piston, that is, when it is moving with only small velocity, and to eliminate entirely the burnt products from the explosion chamber, and at the same time to utilise the vacuum produced by the condensation of the gases. The engine is furnished with a certain number of combustion chambers (generally six), arranged as are the chambers of a revolving firearm. Each of these chambers having been filled with air, then with gas, passes in its revolution before the igniting flame, and the vacuum, determined by the previous forward movement of the piston, inspires the igniting flame and produces the explosion. The forward face of the piston communicates at the same time with the compartment of the revolver immediately preceding that which is in action, and by the action of the air clears this chamber, just used, of the products of combustion. This very logical idea is, however, rendered nearly nugatory by the cumbrous nature of the additional moving parts.

This inventor also has proposed to utilise the explosion of a detonating gas to compress air, afterwards employed to work a compressed-air engine. The idea is ingenious, but has not had any practical demonstration.

In another design this inventor leads the gas into an explosion-chamber, forming a prolongation of the cylinder, by a pipe which passes through the chamber and is pierced laterally with holes.

Northcott's engine (patent No. 3176, of 1880) is characterised in its working by the expansion of a mass of air compressed at each explosion. It is therefore strictly belonging to that *mixed* class of motors of which as yet we have had little experience.

The **Economic Motor Company of New York**, have recently introduced an engine into this country, patented in 1883, No. 4260, in which there is employed a novel cylindrical slide distributor. The engine itself is, however, for a small motor, very complex.

Besides these engines, of which we have given short descriptions of their salient points, are those of **Linford and Cooke**, patent No. 326, of 1883 ; **P. F. Forest**, patent No. 19, of 1883 ; **S. Withers**, patent No. 417, of 1882 ; **Ch. Emmet**, patent No. 397, of 1882 ; **W. B. Hutchinson**, patent No. 2339, of 1882 ; and of **W. W. Tonkin**, patent No. 5201, of 1881. All these inventions are more or less well known to the engineering public and embrace improvements in details, having, of course, considerable importance from the mechanician's point of view. As our space allows of our dealing only with general principles, we are compelled to pass these by.

Resumé of this Part.

Enough has been said up to this point of the gas engine, generally and particularly, to enable the reader to grasp a distinct idea of its action, in its simplest form, and of the essential parts or organs involved; its mechanism for igniting, and for distributing the gas and air.

The **distribution** is effected by an organ very closely related to the slide-valve of a steam engine, from which it differs only by the additional means necessary for obtaining ignition of the detonating mixture.

For instance, in some engines counterbalanced cylindrical slides are employed to regulate the admission of gas and air; in others, as in **Haigh** and **Nuttall's**, oscillating cocks are used, or revolving ones, as in **Linford's** and **Tonkin's**, or slides, as in **Bischopp's.** In **Hallewell's** a disc performs this office. The plate slide is found in the largest number.

Ignition of the detonating mixture in motors working without compression of this mixture is, comparatively with the case of those using compression, an easy task. It is generally effected by inspiring or by throwing in a burning jet, which latter is relighted, when blown out, by a permanent auxiliary gas burner; but of these two methods inspiration is most used. At a given point of the stroke, generally a third, the piston uncovers a small orifice closed by a small lid or clack, which the pressure of the atmosphere opens and pushes forward towards the cylinder, at the same time admitting the flame from the burner. This clack ha replaced by a ball or by a bullet; it has, as ngine, been altogether suppressed, but without any great advantage. In other engines the flame for ignition has been strengthened by a device known as an "**exploder**," that is, the mixture is not directly ignited in the cylinder, but a small part of the mixture is detonated in an adjoining and connecting chamber. Auxiliary mechanism is sometimes employed to open and to close the ignition orifice, but the action is best effected by the slide-valve itself, which having in its substance, a small igniting chamber, carries with it a flame from the burner and as well closes the explosion orifice by one movement. **Incandescence** (to be subsequently described) is a source of ignition employed in this type of gas engine we have been considering, in only one instance, that of the **Economic Motor Company.**

The various ideas of inventors are, in this class of motors, very numerous; not only are they exceedingly difficult to classify, because of their diversity, but no one has, as yet, sufficient experience to be able properly to weed out incorrect or erroneous notions from amongst so many that are untried.

Andrew thinks it necessary to admit to the working cylinder a certain quantity of the mixture directly, by simple aspiration, independently of the admission made by the slide, in order partly that the dimensions of the slide may be reduced.

Generally, the return of the piston is considered sufficient to expel the products of combustion, and in some systems a part of these products is allowed always to remain in the cylinder, as a buffer to deaden the shock of the explosion. This is the case in **Schweizer's** engine. On the contrary, in other engines as complete as possible a clearance of the combustion products is aimed at. **Turner** clears out his cylinder by means of a pump after each stroke of the piston; **Robson** effects the clearance by an auxiliary piston; but experience has not yet shown any definite advantage in out-put of energy as due to these precautions.

The various devices to reduce the cumbrous character of the engine, such as are designed by **Benier** and **Lamart** and **Forest**, or to reduce the height, as in **Ravel's** oscillating cylinder machine, do not appear to have met with any great application: in the case of the oscillating cylinder machine, the disadvantages of this kind of cylinder in the steam engine are equally, if not more, applicable to the gas engine.

Many attempts have been made, in this class of engine especially, to **reduce the shock of explosion**: the use of an air-cushion, or a cushion or mixture of poorer gases, before the charge proper, have been proposed and carried into execution, but the end seems difficult to attain. It seems best realised in **Otto and Langen's** engine as improved by **Gilles**, and in **Bischopp's** arrangement.

Cooling of the cylinder has not received that attention in motors working without compression as in the case of the engines of high powers working with compression, for the reason that the heating is considerably less.

The means of **regulation** seem, with this class of engine, to have been adopted from those usual with steam engines; and, similarly, this seems to be the source of the means adopted by **Linford** to obtain **regularity of motion**, namely, by employing more than a single cylinder.

The **cycle** of this first type of motors is characterised by the following periods:

(*a*) Period during which motive power is produced.	(1) Inflow of the mixture of air and gas generally at atmospheric pressure. (2) Explosion of this mixture at constant volume. (3) Expansion.
(*b*) Period of loss or waste-work.	(1) Exhaust of combustion products.

We shall see that this cycle presents, in comparison with that of engines working with compression, as described in Part II., radical inferiority. One point of loss, theoretically, is the low fall of temperature; and other points, such as the small influence of the cylinder walls, &c., are due to the arrangement of parts consequent upon the simplicity aimed at.

PART II.

CHAPTER II.

GAS ENGINES WORKING WITH COMPRESSION.

We can, in this chapter, now that we are better acquainted with the various organs of a gas engine, and their uses, start out with the consideration of the theoretical cycle of the particular class of engine to be described. It embraces the four following periods:

(1.) Compression of the air and gas according to an adiabatic curve;

(2.) Combustion of the mixture under constant pressure;

(3.) Expansion following an adiabatic.

(4.) Exhaust or escape at atmospheric pressure.

Under this cycle we might admit two divisions; one corresponding to Ericson's heat engine, limited by two adiabatics and two lines of equal pressures; and the other corresponding to the type of the hot-air engine of Joule, limited by two adiabatics and two lines of equal volume. With equal compressions, the former subdivision would represent a class of engines having theoretically a lesser approximation to perfection, although this inferiorit

weighed by practi

pointed out by former French and German writers that, with the former class, the influence of the walls of the cylinder is reduced because the temperature of the combustion is lower than the temperature of the explosion in the engines of the latter class; yet this combustion may be effected in a chamber separated from the cylinder, in which chamber greater heat and better protection from radiation may be attained. If this method of combustion, however, introduces complication of the parts of the cylinder, then there would be no practical, as well as no theoretical advantage.

As types of the former class or subdivision, we may cite the engines of **Foulis** (patent No. 180, of 1881; No. 2,422, of 1882); of **W. Livesay** (patent No. 2,927, of 1883); and of **Crowe** (patent No. 2,706, of 1883); but it is unnecessary here to illustrate the class.

As previously stated, the engines of the latter class, to which belong some important introductions to engineering science in this particular, have a cycle that is theoretically identical with that of Joule's hot-air engine, furnishing the maximum of work per unit volume of gas, when the temperature at the end of the expansion is the same as it was at the termination of the compression.

In this important class of gas engines, two divisions have been recognised scientifically, and have strangely been represented by two important manufacturers in trade: we allude to the **Otto** gas engine as representing one division, in which the whole of the four periods of the cycle are performed in the motor cylinder; and to the **Clerk** engine, in which part of the cycle is performed in a pump or separate cylinder.

It has been already pointed out that the drawback to the direct working in opposition to atmospheric engines can only appear justified by practical adoption when essential changes in the principle of the motor—changes of its cycle process—are considered in connection with it. As well as that with these engines the mixture is compressed before ignition, the piston velocity is considerably increased, and the combustion is prolonged. As concerns the first circumstance, smaller dimensions of the cylinder must be allowed as an advantage; also increase of the certainty of ignition, because the single gas particles, which may be considered as floating in the air—or, more generally speaking, in non-combustible parts of the mixture—lie nearer one another in the compressed mixture than in that at only atmospheric tension; consequently the transmission of the flame through the whole is facilitated. We may, therefore, work with a poorer gas mixture, and obtain from it, in consequence, less initial temperature of the expansion, requiring to carry off less heat by cooling.

The piston velocity of the older engines was, as cited, always less than one metre per second; their construction did not allow a greater value, even when the cylinder worked double, for otherwise the recoils from the explosions were too violent, and the strained parts suffered too much. Atmospheric engines, on the other hand, had at the right moment very great piston velocity, as the piston flew up freely; therefore its diminished consumption of gas. Then the temperature arising from the explosion is the same in the atmospheric engines as in those working direct without compression, but it sinks more suddenly with greater velocity of the expansion; there is less time, therefore, to transmit heat to parts of the machine or to the cooler, and a greater part of it may be converted into work. When an atmospheric engine makes thirty-five piston strokes, each one metre, in the minute, its average piston velocity is certainly small—only 0·58 metre. The piston velocity in the outflight period is, however, very considerable, as, according to Meidinger's observations, this takes only one-tenth of the duration of the whole play. We shall see very clearly how great is the influence of the piston velocity; for it is not easily observable that other circumstances should cause an essential difference in the consumption of gas of the atmospheric engine, compared with those working direct without compression. If we could give the latter class of engines the same piston velocity, then the difference would be scarcely apparent.

Otto's Engine.

In Figs. 25 to 37—35 G is represented an eight-horse motor. This is a horizontal arrangement, similar to the usual steam-engine. A is the cylinder provided with a cooling jacket, at one end open, at the other considerably lengthened beyond the inner dead point of the piston. The space thus formed, or so-called combustion chamber, amounts to about two-thirds of the play of the piston. In this part of the cylinder there are two openings, *a* and *b*; *a* for the inlet and the ignition, *b* for the exhaust. The first is opened and closed by the slide B, the latter by the valve C. The piston D transfers the force taken up by piston rod, crosshead, and connecting bar, to the crank shaft, which carries pulley and fly-wheel, and by which the slide movement is promoted through the gearing, the shaft, G, crank, H, and connecting bar, I. The slide cover is pressed by a spiral spring against the slide; two suitable nut-screws secure it when the springs are not of sufficient tension.

The engine is single working. The cylinder serves alternately as compression pump and working cylinder. When the piston moves from the dead point position forward, it draws in the explosive mixture. When it makes its stroke backwards it compresses the mixture; it goes then, for the second time, forward, the explosion follows, and the expansion of the combustible products; when it returns for the second time it drives out the combustible products. The working period, therefore, comprises four half piston strokes, or two revolutions of the engine. The special performance of work only takes place during the third part of the period; during the first, second, and fourth sections a part of the work is again used in the engine; the active force of the fly-wheel must here help out.

In order that this mode of working may be available, the slide makes only half as many strokes as the piston; the wheels E F are as 1 : 2; the governing shaft G runs at only half as many revolutions as the main shaft. The movement of the slide is now as follows in reference to the piston movement, so that it may fulfil its functions of feeding and regulating. In the representation, Fig. 28, let the circle 1, 2, 3, 4 be the cycle of the slide crank, and i, ii iii, iv, that of the piston crank, which, on account of the more convenient view, is supposed to be displaced in the plane of the first. As now in the initial position of the working period, the slide crank lies towards the piston crank at about 45°, and as it makes only half as many revolutions as the latter, the positions 1, 2, 3, 4 correspond with the positions i., ii., iii., iv. During the first piston stroke i. ii., the slide goes from its first position, *a*, into the dead point B, and from this into the first again, corresponding to the action of the slide crank 1, 2. This movement accomplishes the filling. During the second piston stroke, ii. iii., the piston compresses the mixture in the cylinder; the slide, the crank of which goes from 2 to 3, keeps the engine closed; whilst the third piston stroke iii., iv., causes the explosion and expansion of the combustion products. The slide must, therefore, after it has passed the position gained, effect the ignition; then, whilst it returns through its dead point behind 8, into the same position, corresponding to the crank action 3, 4, keep the engine closed. The same is the case when the fourth piston stroke, 4, 1, occurs, corresponding to the crank movement 3, 4, because the driving out of the combustion products does not take place through the slide, but through the exhaust valve.

In order to be able to fulfil these conditions, the slide is arranged as Figs. 29 to 35 represent. Fig. 29 shows a horizontal section through the back part of the cylinder, as the height of the centre line, and the marked position is that which the slide must occupy at the beginning of the first period; therefore position 1. If it now goes from left to right in the first half of the first period, the air streams out of the space *c*, which is in connection with the external atmosphere, through the conduit *d* into the opening *a*, whilst the gas comes out of the space *e* of the slide cover through a series of fine openings, *f*, lying one above another, and mixes here with the air.

Ignition is effected in the following manner. There is in the slide valve a chamber which communicates immediately with an especial gas conductor on the cover shortly before position 3. This chamber is, therefore, filled with gas, and serves for the formation of a connecting flame between the ignition flame, always burning in the cavity of the slide cover, and the charge; such a connection is necessary, because the charge at the time of the ignition possesses a higher tension, and, therefore, cannot communicate with an open burning flame. If now the connection chamber is filled with gas and air, the mixture is ignited at the ignition flame; afterwards this connection is cut off, and then communication restored, through quite a narrow conduit, between the connecting flame and charge. As the conduit is so very narrow, the flame is not extinguished in the chamber by the passage of a strongly tensioned charge, and the tension is equalised, so that immediately the mediating chamber gets into connection with the further opening *a* of the cylinder the flame strikes into the charge, and may cause it to explode.

In immediate proximity of position 3 there must take place three consecutive circumstances: (1) formation and ignition of the mediating flame; (2) equalising the tension; (3) ignition.

Fig. 30, a vertical section on *x y* in Fig. 29, represents the source of the mediating flame. In the slide there is the chamber *g*; this communicates with the flue *h*, placed at the slide cover. The ignition flame burns in the flue *h*, at the opening of it, which facilitates the entrance of air. Into the chamber *g* the mouth of the conduit *k* opens, and to this the conduit *l*, in the slide cover, leads the gas which fills the chamber and ignites the burning flame in the cover. Through the further movement of the slide, it attains the position Fig. 31; here occurs, by the small conduit mouth *m*, on the connection with the interior of the cylinder, the equalising of the tensions. A little further continuation of movement of the slide allows *g* to meet with the greater opening *a* and effect the ignition.

It is clear that these positions also occur on the reversal of the slide *c*, in reversed succession, and that in consequence a slight blowing out of the combustion product takes place from the cylinder through the mediating chamber into the ignition flame, and a little gas current out of *l* upon the same stroke; both are not, however, of importance, effecting only slight flickering of the ignition flame. Figs. 32 to 35 give views of the valve face, both at slide surface, and the slide cover; they require no explanation, 33 and 35 are drawn reversed on account of the better view.

The regulating of the engine is very ingenious. It was previously pointed out that it is necessary to take care, in the governing, that the mixture of the gas and air, required for combustion, is in proper measure. That is not possible with a valve on the gas pipe, which is closed more or less by a centrifugal regulator. Otto has therefore preferred so to arrange the regulating valve, that it either provides for the entrance of the proper gas mixture, or admits no gas at all into the engine, so that this runs empty, or only draws in air, compressing, expanding, and expelling it. The arrangement is shown Fig. 25 and 27 K; the regulating valve in question is represented in detail in Fig. 36. It is kept closed by a spring *n*, and only opens when a spoke *o* of the cam *p* placed upon the governing shaft lifts the one limb of the angle lever *g*, the other limb of which leans against the valve bar. This takes place quite regularly with normal action of the engine; so soon, however, as it goes too quickly, and the balls of the regulator L rise, the angle lever *r* moves the cam *p* so far aside as to allow the spoke to pass the leg of the angle lever. No gas can now enter until the balls of the regulator have again sunk; a series of explosions occur. In order that the valve K may not remain open on the stoppage of the engine, and also that the gas pipe may be securely closed, the arrangement is so regulated that when the balls of the governor are quite down, the cam *p* is moved aside to the right, so that the spoke can never stand under the angle lever *g*. The consequence of this would be, that the machine must be turned so fast in running that the balls of the governor would rise, a matter of impracticability. There is, therefore, the small rotary support *s* provided; this is set up before the engine is put into motion and the cam *p* moved into the right position; as soon as the explosion occurs, the support is free and falls down.

The exhaust valve c, which is represented in detail in Fig. 37, is controlled by the governor shaft through the cam *t*; this carries a catch which presses back at the appropriate time the angle lever *u*, which lies lightly against the cam by spring pressure and generally holds the valve closed. Because, however, the engine is turned with difficulty when the compression is to be overcome, there is arranged upon the cam *t* a second catch *o*, placed about 180° with the first, and half as broad as this, which operates, in regular action upon the angle lever *u*, and thus upon the valve *g*. If, however, the cam is pushed to the right by the hand lever *v*, then the valve opens twice in one period—namely, during the discharge and during the compression. The engine now runs easily; and as soon as it gets into motion the hand lever is again reversed.

After this description, the action of the engine may be understood up to one point—the arrangement for the attainment of a slow combustion. The whole gas mixture does not explode at once, but only a part of it; the rest then burns away gradually, whilst the piston moves forward. That this, in fact, is the case may be concluded from the indicator diagram; this also shows that, with the expansion, an additional heat occurs, which cannot be explained otherwise than by the phenomenon of the "after" combustion. The cause of this phenomenon, to the importance of which attention has already been drawn, is to be sought in the large combustion space in which, at the end of every working period, great quantities of combustion products remain. **Slaby,**[*] and probably Otto himself, accept the following explanation. As behind the piston, in its first dead-point position, combustible products entirely are to be found, and as the piston in the forward action, at the beginning, draws in only air, and only, later on, a combustible gas mixture, these gases do not mix equally—there is a stronger mixture collected at the foot of the cylinder than further towards the piston, and this inequality is not entirely removed by the compression now following. The violent mediating flame now strikes like a shot into the cylinder, and effects the explosion of the rich gas layers behind. During the action of the piston, the gradual combustion occurs of the further gas particles in the mixture of air and residuum lying in front; the cushion of indifferent gases lying in the immediate proximity to the piston modifies, at the same time, the blow upon this. There is no question that this explanation would be completely satisfactory if the stratified positions of the gas were known; the absolute assumption of it, however, would be somewhat bold. **Wedding**[†] maintains that the after combustion occurs according to Bunsen's law: thus only so much gas is consumed as belongs to the production of a temperature, at which the dissociation of the combustible product must take place. Yet it is not easily perceivable why, with a mixture containing no residuum, how it was expended in the old direct-working engine, no after combustion taking place.

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[*] Sitzungsbericht des zur Vereins Beförderung des Gewerbfleisses in Preussen, 3 March, 1879.

[†] Pogg. Annalen, Vol. 131, p. 161.

In the general disposition of such an engine, the gas-pipe has one (with larger engines there are two) rubber bag interposed, in order to protect the contents of the pipe from the suction of the engine. The gas-pipes for the ignition flames have to branch off from before the rubber bags, in order that these flames may burn quietly. The application of a gas pressure regulator is also desirable. The air is best taken from a suction vessel, so that no impurities can come into the engine, and noise may be avoided. In order to avoid the violent detonation, or so as to make it less loud, an outlet valve is inserted in the exhaust-pipe.

If there is sufficient water for the procedure, it may be allowed to flow continuously through the cooling jacket. If a cistern is used to which the heated water is returned, the source of the supply must hold one cubic metre per horse-power. The arrangement at starting is as follows :—The support *s* is set up at the regulator; the compression thrown out of gear; the cold-water pipe opened; both taps of the ignition flame opened and the flame ignited, the tap arranged as may be most suitable to correspond with the pressure of gas; and the engine is now brought into action by a sudden turn of the fly-wheel. The regulating tap is opened now by degrees, and finally the transmission belting is thrown in gear.

The care of the engine is simple; it requires very little attention. The principal care is good oiling for the cylinder and slides ; this is secured by a self-acting arrangement. In the grease vessel L, Fig. 25, there is a small chain pump, driven by a cord off the governing shaft, and this moves the oil in drops to the front end of the cylinder and the pipe leading to the slide boxes. For the sake of good maintenance, it is well, as a rule, to take the slide asunder every week, and to clean it ; every two weeks to remove the piston, and to examine the whole engine thoroughly. This work requires respectively two and eight hours time. The necessity for oiling is very small ; the possessor of an eight-horse power engine states that he uses in thirty working hours one kilogramme, consisting of three quarters rape oil, and one quarter petroleum. The communication of the following hint may perhaps be welcome to many. It happens occasionally that the engine will not move at all ; after some time, however, it freely moves. This may probably happen from a little oil being in the trough of the slide cover, through which the gas streams for the mediating flame, and making it difficult for the gas to approach.

Notwithstanding the engine is only single working, it goes very regularly, particularly with a heavy load. Suction takes place with pressure a little under 1 atmosphere, the compression shows 3 atmospheres ; through the explosion the tension is sent up to about 11 atmospheres, and sinks gradually again, in consequence of the expansion to 3 atmospheres, then the outlet valve opens at about 10 per cent. of the piston stroke before the dead point; at the dead point the tension is close upon 1 atmosphere, and remains so to the end of the working period; the gases escape at fully 400°. From the diagrams it is conclusive that the highest temperature is 900 or 1,000°.

The consumption of gas may be taken at 1 cubic metre per horse and hour; naturally with large engines relatively less than with smaller. By experiments we find occasionally smaller quantities; it must be remembered, however, that in such cases the engines are usually thoroughly cleaned; for ordinary working one will not make a mistake with the above figure.

In the following tables* are the results of a series of brake experiments, which have been taken with such engines. The experiments 6—16 especially, will show how beautifully the regulation works; the figures for the consumption of gas per hour and horse-power increase only slowly with decreasing work requirements. The influence of cooling is visible with experiments 11 and 13—16, the temperature of which was maintained at 65—75°; with experiment 12, however, at 32—38° Whilst the other data in 12 and 13 agree pretty closely, the consumption of gas in the first case is higher than in the last. With experiment 14 the cooling water was measured; it gave with an increase of temperature of 12—17°, a consumption of 175 litres hourly. The influence of the gas pressure, which

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* Schöttler's Gas-Machine, p. 49.

TABLE OF BRAKE TRIALS.

No.	Description of Engine.	Observers.	Duration of Trial.	Length of Lever-arm.	Load.	Number of Revolutions.	Number of Explosions.	Brake-power.	Gas consump.	
									Hourly.	per hour and h. p.
	h. p.		Min.	m.	kg.	per minute.		h. p.	litres.	litres.
1	2	Brauer & Slaby, Berlin ... ... 6./12.78.	60	1,219	7,8	172,1	0	2,29	2300	1005
2	2	,, Festigkeits-Laboratory... ... 21./3.78.	30	1,000	8,3	180,0	13,0	2,08	2500	1200
3	2	,, ,, ... ,,	60	,,	4,0	184,0	48,0	1,03	1500	1460
4	4	,, Exhibition in Erfurt ... ... 12./8.78.	92	,,	—	159,4	0,7	3,98	4250	1070
5	4	Brauer & Schöttler, Exhibition in Altona ... 5./9.81.	65	0,831	21,5	158,8	—	3,96	3590	912
6	4	Frese & Schöttler, Techn. High School, Hanover 23./7.81.	17	1,462	13,05	144,2	0	3,84	4182	1089
7	4	,, ,, ,,	20,5	,,	9,05	155,8	17,6	2,88	3541	1229
8	4	,, ,, ,,	20,5	,,	5,05	157,4	34,9	1,62	2956	1825
9	4	,, ,, ,,	23,5	,,	1,05	157,9	48,1	0,34	1813	5333
10	4	,, ,, ,,	20	,,	0	159,7	58,0	0	1230	∞
11	4	,, ,, 10./12.81.	20	0,840	23,15	182,4[5]	0	4,95	4725	955
12	4	,, ,, ,,	20	,,	,,	160,0	3,0	4,34	4455	1026
13	4	,, ,, ,,	25	,,	,,	159,5	1,7	4,33	4212	973
14	4	,, ,, ,,	45	,,	21,65	157,0	4,0	3,99	4112	1031
15	4	,, ,, ,,	20	,,	15,15	160,7	21,2	2,86	3285	1148
	4	,, ,, ,,	20	,,	0	161,6	60,2	0	1170	∞
		Brauer & Schöttler, Exhibition in Altona ... 3./9.81.	60	1,105	55,0	138,0	—	11,8	11500	975

varied from 18—24 mm. water pressure, could not be established.

Professor Thurston's Experiments.

Previously to the results obtained by Messrs. Morgan Brooks and J. E. Steward detailed further on, Professor Thurston found from trials with gas engines of various size and design that the consumption of water-gas varied from 21·2 to 23·4 cubic ft. per horse-power per hour, in engines of 6 to 7 indicated horse-power, up to 23·5 to 24·5 cubic feet in an engine of 2 horse-power or less.

Friction of mechanism absorbed ... 4·5 % total energy combustion;
or from 40 % power in smaller } engines.
to 20 % ,, larger
Waste at exhaust 12 % total heat of combust. small } engines.
,, ,, 24 % ,, ,, large
or from 100 % } heat transformed into useful work.
,, 200 %

In one case the distribution of heat of combustion was as follows.

Useful dynamometric work	14·27
Work of pump	·42
Friction of mechanism ...	4·10
Lost in exhaust	23·55
Lost in water jacket ...	46·90
Radiation, &c.	10·76
Heat supplied ...	100·00

Engine,
7 H-P. brake;
8·9 H-P. indicator.

Gas consumed,
21·2 H-P. H. ind.;
27·6 H-P. H. brake.

The following are the principal dimensions of the Otto engine used by Messrs. Morgan and Steward.

Piston stroke	356 mm.
Diameter	216 mm.
Diameter of brake pulley	762 mm.
Length of friction lever	420 mm.
Weight of two fly-wheels	750 kilog.

Volume of compression chamber 38 per cent. of total volume of cylinder.

The supply of air was measured, as well as of that of gas, so that their proportions might be accurately known and not derived from calculation.

The temperatures of water entering and issuing from the cylinder jacket and of the exhaust gases are given.

Gas pressure	1¼ inches, or	30 mm.
Air „	2 „	50 mm.

Summary of Tests. The "horse-power in gas burned" was calculated from the analysis of Hoboken gas, and is the dynamic equivalent of the heat capacity of the gas. The "horse-power lost by exhaust," and "by water jacket," were calculated from the specific heats of the discharged gases and of water. The indicated horse-power was computed in the ordinary way from the number of explosions and the mean effective pressure. The area of the cards between the compression and expansion lines was measured with an Amsler planimeter. An allowance was made for the area between the exhaust and admission lines, representing work done in expelling the burned gases, and in drawing in the fresh charge. This allowance is equivalent to a little more than one-tenth of an atmosphere mean effective pressure.

Friction of Engine.—The difference between the indicated and the actual work gives the amount of friction in the engine. In tests 10 and 17 this falls below 15 per cent of the indicated work, a somewhat doubtful figure. The average of all the tests at full power is 18·6 per cent friction, a remarkably good result.

The gas used gave on combustion 5·495 calories per cubic metre according to ordinary calculation, and was used at a temperature of 24° C. A richer gas, or one used at a lower temperature would give greater power for the same volume.

The table of results, at varying power gives the results of tests made when there was not sufficient resistance to make the engine take gas every time. This is the ordinary condition of running, for it is well for the governor to have a reserve of power to draw on. The gas consumption per indicated horse-power with varying power is nearly constant, but per actual horse-power increases, since the ratio of friction to useful work is greater. The advantage of the governor in ensuring the greatest possible economy, when the engine is not moving at full power, is thus shown.

Ratio of Air to Gas.—The ratio of air to gas was found by actual measurement of both, to be about seven to one, when the engine was working most economically. Although with better gas the ratio would be slightly increased, yet it could not equal that usually given for the Otto engine, ten to one, or thereabouts.

The ratio is commonly obtained from a measurement of the gas consumption alone, the air being reckoned as the volume of the piston displacement, less the measured amount of gas.

This is not an accurate method, as is shown by the indicator diagram (Fig. 38). The pressure in the cylinder is sensibly below the atmospheric at the end of the out stroke, and it is manifestly unfair to compare volumes when the pressures are different. If, however, the volume represented on the indicator card between the points 1 and 3 (at which points the gases enclosed in the cylinder are at atmospheric pressure) be used in calculation, instead of the entire piston displacement, a much closer result will be obtained. The ratio determined by means of two meters, is however, much more satisfactory than a calculated result.

When the proportion of air is increased by partly closing the gas valve, the card obtained is like B or C (Fig. 39); the explosion line is much more inclined, the mean effective pressure is less, consequently also the indicated horse-power.

The gas consumption per indicated horse-power is not much changed, but per effective horse-power it becomes considerably greater, showing the false economy of throttling the gas supply. A comparison of tests 16 and 20, in which the conditions other than the ratio of air to gas are nearly identical, shows very plainly the disadvantage of using too little gas.

A careful comparison of the results fails to show that any marked difference in either the indicated or actual work is caused by varying the temperature of the water jacket, the greater direct radiation with warm water balancing the greater amount of heat carried off by cooler water.

In the calculation,

$$\gamma = \frac{Cp}{Cv} = 1{\cdot}37.$$

Specific heats of gases are not supposed to be greater with higher temperatures.

THE INDICATOR DIAGRAMS.—The indicator diagram, Fig. 40, is a fair sample of those taken during the tests at full power. Beginning at the point 1, the lowest line of the diagram represents the pressure during the first forward stroke, while gas and air are entering the cylinder. This line lies at a nearly uniform distance below the atmospheric line, as is shown more clearly on the diagrams taken with a very slight spring. This line, 1, 2, shows a negative pressure of about 0·15 atmosphere. At 2 the inlet valve closes, and by the return stroke the gases are compressed into the clearance space at the back end of the cylinder. This compression is represented by the line 2, 3, 4, 5, which crosses the atmospheric line at 3, and shows a pressure of 2 atmospheres at 5. One revolution of the engine is now completed and the charge is ignited just as the crank is passing the centre. The rapid burning of the gas liberates a large amount of heat, increasing the temperature and pressure, which reaches about 9 atmospheres as a maximum. The line 5, 6 is called the explosion line, although the action is better described as rapid combustion than as an explosion. The gases now expand during the second forward stroke, and exert upon the piston energy which, by means of the fly-wheels, carries the engine through the remainder of the cycle. At 7 the exhaust valve opens, allowing the burned gases to escape. The line 8, 1 shows the pressure while these gases are being expelled by the second return stroke of the piston.

When the governor prevents the admission of gas to the cylinder the cycle is somewhat modified. After compression of the air no explosion can take place, since there is no combustible mixture present. The expansion line then follows closely the previous compression line, and the cycle is completed by expulsion of the air. Two revolutions are required to complete the cycle when the engine takes gas at every charge; and four, six, eight, or sometimes ten revolutions may occur before the engine returns to its original state.

In Fig. 4 are given copies of two cards: one A taken during test 1, when the engine took gas every time. Since in test 1 four charges of air passed through the cylinder after every explosion, the products of combustion were almost completely expelled, leaving the clearance space filled with nearly pure air at a temperature little above the atmosphere. A larger charge of gas could thus be drawn into the cylinder and still have sufficient oxygen for combustion. The result is shown by the greater area of diagram A. The mean effective pressure is not, however, proportionately greater, since the correction for work done in drawing in gases has to be applied five times to A, and only once to B.

It will be noticed especially by a light spring diagram that the pressure between the points 9 and 10 falls below the atmospheric. This is undoubtedly due to the rapid cooling of the hot discharged gases in the exhaust vessel and pipe outside the engine. The contraction of these gases from this cooling is greater than the piston displacement during the early part of the return stroke, thus causing a partial vacuum within the cylinder. To show that this is the real cause, and that it is not due to any inaccuracy of the indicator, a diagram was taken when the engine was running without taking gas every time. After an explosion the pencil follows the lines, *a*, *b*, *c*, *d*, the same as 8, 9, 10, 1, on the other diagram. During the next forward stroke no gas is taken in, and the line, *d*, *e*, corresponding to 1, 2, is drawn. Then follows the compression line, *e*, *f*, *g*, *h*, the same as 2, 3, 4, 5. Since there is no explosion this time, the pencil returns along the wave line, *i*, *j*, *k*, *l*, nearly coincident with the compression line. At *m*, the exhaust valve opens, allowing air to enter from without. The pencil does not return to *e*, but moves to *n*, nearly on the atmospheric line. Since the gases have not been heated, there can be no contraction to counteract the piston displacement, and on the return stroke the exhaust line, *n*, *o*, *p*, *q*, immediately rises above the atmospheric, as would be inferred. That it keeps above the other exhaust line, *b*, *c*, *d*, for the whole length of the stroke is a further confirmation of this reasoning.

The authors account for the expansion line being adiabatic, or nearly so, by continued combustion of portions of gas previously prevented from combining by high temperature, and accept the dissociation theory, and add it is quite possible that the gas is not fully burned until after the opening of the exhaust valve.

EFFICIENCY.—As the cycle in which a gas engine works does not even approximate to the theoretical cycle of Carnot, it seems futile to apply his formula for efficiency.

The indicated work represents 18 per cent of the total heat of combustion of the gas. The useful actual work is 14½ per cent.

An efficiency sometimes given for the Gas Engine, derived from the indicator diagram alone, is the indicated work divided by the indicated heat, giving about 80 per cent. This is manifestly incorrect, since the indicated heat is not the whole heat of the gas.

The best steam engines utilise only 10 per cent of the total heat of combustion of the coal, and small engines rarely exceed 5 per cent., so that the gas engine is by far the more perfect heat engine.

Disposition of the Heat.—Heat is disposed of in a gas engine in these ways:

(1.) As indicated work, including useful work and friction.
(2.) In the hot expelled gases.
(3.) In the water jacket.
(4.) In radiation, &c.

Taking the figures directly from test 19, but making allowance for probable error in the figure for water-jacket, it is found that—

(1.) = 1·33 calories, or 17 per cent.
(2.) = 1·18 „ 15½ „
(3.) = 4·00 „ 52 „
(4.) = 1·18 „ 15½ „

the sum 7·69 calories, being the total heat of combustion of the gas.

Relative Economy of Gas, Steam and Hot Air Engines.—In making a comparison of this kind it is necessary to consider

(1.) The cost of gas or coal consumed.
(2.) The cost of water used.
(3.) Lubrication.
(4.) The cost of attendance.
(5.) Depreciation and repairs.
(6.) Interest on capital invested.

(1.) The average consumption of gas in a gas engine per effective horse-power per hour, including igniting flames, is about 30 cubic feet.

The consumption of coal per effective horse-power per hour by small steam engines is about 7 lbs.

(2.) The water used in the water-jacket of a gas engine will not enter into the estimate, since by the use of tanks the same water may be used continuously.

The water supplied to the boiler of the steam engine here considered amounts to $\frac{5}{8}$ cubic foot per horse-power per hour.

(4.) A gas engine requires little or no attendance. A man can accomplish $\frac{5}{6}$ of a day's work and still take full charge.

Steam engines of this size require from $\frac{1}{2}$ to 1 day's attention, depending upon the proximity of the engine and boiler.

(5.) As regards depreciation, it is safe to say that gas and steam engines have about equal terms of life; for, while gas engines have less complication of working parts than steam engines, yet they are subject to more severe and abrupt strains.

(6.) The interest will necessarily be directly proportional to the amount of capital invested.

The following summary shows the relative cost of a day's running, in America where the tests were made:

GAS ENGINE, 8 H.P. ACTUAL, 10 HOURS.

(1.)	2,400 cubic feet gas @ $2.50 per 1,000...	$6.00
(2.)	Water	0.00
(3.)	Lubrication	0.20
(4.)	$\frac{1}{6}$ day's labour @ $2.00	0.33
(5.)	Depreciation, &c., @ 12 per cent. per year, $\frac{12}{360}$ per cent. on $1,075 ...	0.36
(6.)	Interest at 5 per cent. per year, $\frac{5}{360}$ per cent. on $1,075	0.15
	Daily expense	$7.04

STEAM ENGINE, 8 H.P. ACTUAL, 10 HOURS.

(1.)	Coal, $\frac{560}{2240}$ tons @ $5.00	$1.25
(2.)	Feed water, 65 cub. ft. @ $1.25 per 1,000	0.08
(3.)	Lubrication	0.15
(4.)	$\frac{1}{2}$ day's labour at $2.00	1.00
(5.)	Depreciation, &c., at 12 per cent. per year, $\frac{12}{360}$ per cent. on $800	0.27
(6.)	Interest at 5 per cent. per year, $\frac{5}{360}$ per cent. on $800	0.11
	Daily expense	$2.86

The following figures have been obtained for the expense of running a small hot-air engine. This engine has been running in a printing office in New York City for 18 years. It uses $4\frac{1}{2}$ lbs. of coal per horse-power per hour; every third year relining costs $100.

HOT-AIR ENGINE, $2\frac{1}{2}$ H.P. ACTUAL, 10 HOURS.

(1.)	Coal, $\frac{115}{2240}$ tons @ $5.00	$0.25
(2.)	Water	0.00
(3.)	Lubrication	0.10
(4.)	Attendance same as for gas engine	0.33
(5.)	Depreciation, &c., @ 10 per cent. per year, $\frac{10}{360}$ per cent. on $750	0.21
(6.)	Interest @ 5 per cent. per year, $\frac{5}{360}$ per cent on $750	0.10
	Daily expense	$0.99

The cost of one horse-power per hour is,

With gas engine	$8\frac{3}{4}$ cents.
With steam engine	$3\frac{1}{2}$ cents.
With hot-air engine	4 cents.

For intermittent work the gas engine is much more economical than the above figures indicate; and this fact, together with its safety, cleanliness and convenience, makes the gas engine very desirable where small powers are required.

The original and classic type of the Otto engine has received improvements at the hands of both its German and English manufacturers. Otto himself, according to his English patent of 1881 (No. 60) has proposed, when dealing with gas of lower combustion power than ordinary lighting gas, to completely remove the products of combustion, by the aid of an auxiliary piston, which piston is situated in the rear end of the cylinder and is returned by a spring acting under the action of a cam and levers.

Crossley's Engine.

In the first type of this improvement on the Otto engine patented in 1880 (No. 4,297) explosion occurred only once in two revolutions, and the products of combustion were removed by a pump supplying a flow of air under a low pressure.

In the second type of engine patented by Crossley in 1881 (No. 5,469) there is an explosion at each revolution. After the explosion, the motor-piston allows a part of the products of the explosion, at a certain point in the stroke, to escape directly into the atmosphere. At this point, the slide valve puts the cylinder into connection with a chamber in which a suction pump has determined a certain amount of vacuum. At the same time the cylinder receives the explosive mixture of gas and air preceded by a mass of pure air to prevent an explosion. Then the motor-piston un-

TABLE OF TRIALS. (*See* pages 70–81.)

Number of Test.	At varying powers.								
	1.	2.	3.	4.	5.	6.	7.	8.	9.
Duration, in mins.	15	15	30	14·5	30	10	15	10	60
Gas, in litres	355	495	1785	1175	2805	805	1310	980	7050
Air ,,	10900	—	—	—	—	7850	11800	8000	43550
Ratio of air to gas	—	—	—	—	—	—	—	—	—
Amount of water through water jacket (litres)	26·5	131	122	113	306	71	107	69·5	690
Temperature of water in °C entering	22	22	21	21	21	22	22	22	22
Temperature of water in °C leaving	49	29	51·7	44·5	42	49·5	48	51	45·7
Number of double revolutions	1252	1247	2445	1184	2426	809	1212	801	4634
,, revolutions per min.	167	166	163	163	162	162	162	160	154·5
,, explosions	235	352	1224	788	1820	607	970	716	4620
Ratio of explosion to double revs.	·19	·3	·5	·66	·75	·75	·8	·89	·997
Average weight on brake arm (kilos.)	0	0	29	48	57	49	57	68	83
Mean effective pressure (atmospheres)	4·2	3·3	4·24	4·3	4·1	4·0	3·9	4·0	4·2
Temperature of exhaust gases (°C)	163	121	299	349	371	371	366	402	416
Indicated horse-power	2	2·55	5·4	7·06	7·6	7·3	7·6	8·6	9·4
Effective brake horse-power	0	0	2·73	4·5	5·3	4·5	5·4	6·3	7·6
Horse-power lost by exhaust gases	2·3	—	—	—	—	6·7	6·8	7·6	7·6
,, ,, water jacket	6·6	8·1	11·5	16·8	19·8	18	17·	18·7	25·2
,, ,, gas burned	12·2	17·1	30·9	42·1	48·5	41·9	45·6	51	61
Gas per indicated H-P. per hour (litres)	708	765	660	697	736	663	604	685	745
,, effective ,, ,, ,,	—	—	1310	1090	1060	1080	970	940	930

TABLE OF TRIALS. (*See* pages 70–81.)

Number of Test.	At full power.										
	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
Duration in mins..................	30	30	30	30	30	30	30	25	20	10	30
Gas in litres	3090	3255	3460	2975	3227	3255	3320	2520	2040	1050	2975
Air ,, ...	20740	22850	21670	22540	23510	23040	22850	17650	14050	16940	22910
Ratio of air to gas	6·6	6·9	6·2	7·4	7·1	7·0	6·86	7·0	6·9	6·63	7·7
Amount of water through water jacket .... (litres)	221	325	170	188	127	248	334	82	58	116	276
Temperature of water in °C .... entering	22	22	22	22	22	22	23	23	23	23	24
leaving	59·7	48	80	76	80	57	49	89·4	88·2	53	48·1
Number of double revolutions...	2100	2325	2299	2291	2461	2404	2374	1859	1472	750	2396
,, revolutions per min.	140	155	153	153	164	160	158	149	147	150	160
,, explosions	An explosion every two turns.										
Ratio of explosion to double revs.	1	1	1	1	1	1	1	1	1	1	1
Average wt. on brake arm (kilos.)	89	85	87	81	81	80	88	86	86	85	68
Mean effective pressure (atmos.)	4·2	4·1	4·1	3·9	3·9	3·8	4·04	3·85	3·97	4·15	3·5
Temperature of exhaust gases (°C)	399	429	432	427	427	432	430	422	407	410	421
Indicated horse-power	8·4	9·6	9·5	8·9	9·7	9·6	9·6	8·7	8·7	9·3	8·5
Effective brake horse-power	7·2	7·8	7·8	7·1	7·7	7·5	8·1	7·4	7·2	7·4	6·3
Horse-power lost by exhaust gases	6·9	7·9	7·8	7·7	8·1	8·0	8·0	7·3	7·0	7·0	7·8
,, ,, water jacket...	25·7	26·2	30·5	31·2	22·4	26·8	26·9	20·3	17·6	33·4	20·6
,, ,, gas burned ...	53·4	56·4	59·8	51·5	55·9	56·4	57·6	52·3	52·9	54·4	51·5
Gas per indicated H-P. H. (litres)	735	680	725	668	665	694	687	700	677	703	—
,, effective ,, ,,	851	835	892	835	832	850	825	822	850	853	946

TABLE OF TRIALS. (*See* pages 70–81.)

Number of Test.	At varying powers.								
	1.	2.	3.	4.	5.	6.	7.	8.	9.
Duration, in mins.	15	15	30	14·5	30	10	15	10	60
Gas, in litres	355	495	1785	1175	2805	805	1310	980	7050
Air ,,	10900	—	—	—	—	7850	11800	8000	43550
Ratio of air to gas	—	—	—	—	—	—	—	—	—
Amount of water through water jacket (litres)	26·5	131	122	113	306	71	107	69·5	690
Temperature of water in °C entering	22	22	21	21	21	22	22	22	22
leaving	49	29	51·7	44·5	42	49·5	48	51	45·7
Number of double revolutions	1252	1247	2445	1184	2426	809	1212	801	4634
,, revolutions per min.	167	166	163	163	162	162	162	160	154·5
,, explosions	235	352	1224	788	1820	607	970	716	4620
Ratio of explosion to double revs.	·19	·3	·5	·66	·75	·75	·8	·89	·997
Average weight on brake arm (kilos.)	0	0	29	48	57	49	57	68	83
Mean effective pressure (atmospheres)	4·2	3·3	4·24	4·3	4·1	4·0	3·9	4·0	4·2
Temperature of exhaust gases (°C)	163	121	299	349	371	371	366	402	416
Indicated horse-power	2	2·55	5·4	7·06	7·6	7·3	7·6	8·6	9·4
Effective brake horse-power	0	0	2·73	4·5	5·3	4·5	5·4	6·3	7·6
Horse-power lost by exhaust gases	2·3	—	—	—	—	6·7	6·8	7·6	7·6
,, ,, water jacket	6·6	8·1	11·5	16·8	19·8	18	17·	18·7	25·2
,, ,, gas burned	12·2	17·1	30·9	42·1	48·5	41·9	45·6	51	61
Gas per indicated H-P. per hour (litres)	708	765	660	697	736	663	604	685	745
,, effective ,, ,, ,,	—	—	1310	1090	1060	1080	970	940	930

TABLE OF TRIALS. (*See* pages 70–81.)

Number of Test.	At full power.										
	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
Duration in mins.	30	30	30	30	30	30	30	25	20	10	30
Gas in litres	3090	3255	3460	2975	3227	3255	3320	2520	2040	1050	2975
Air ,,	20740	22850	21670	22540	23510	23040	22850	17650	14050	16940	22910
Ratio of air to gas	6·6	6·9	6·2	7·4	7·1	7·0	6·86	7·0	6·9	6·63	7·7
Amount of water through water jacket (litres)	221	325	170	188	127	248	334	82	58	116	276
Temperature of water in °C entering	22	22	22	22	22	22	23	23	23	23	24
Temperature of water in °C leaving	59·7	48	80	76	80	57	49	89·4	88·2	53	48·1
Number of double revolutions	2100	2325	2299	2291	2461	2404	2374	1859	1472	750	2396
,, revolutions per min.	140	155	153	153	164	160	158	149	147	150	160
,, explosions	An explosion every two turns.										
Ratio of explosion to double revs.	1	1	1	1	1	1	1	1	1	1	1
Average wt. on brake arm (kilos.)	89	85	87	81	81	80	88	86	86	85	68
Mean effective pressure (atmos.)	4·2	4·1	4·1	3·9	3·9	3·8	4·04	3·85	3·97	4·15	3·5
Temperature of exhaust gases (°C)	399	429	432	427	427	432	430	422	407	410	421
Indicated horse-power	8·4	9·6	9·5	8·9	9·7	9·6	9·6	8·7	8·7	9·3	8·5
Effective brake horse-power	7·2	7·8	7·8	7·1	7·7	7·5	8·1	7·4	7·2	7·4	6·3
Horse-power lost by exhaust gases	6·9	7·9	7·8	7·7	8·1	8·0	8·0	7·3	7·0	7·0	7·8
,, ,, water jacket	25·7	26·2	30·5	31·2	22·4	26·8	26·9	20·3	17·6	33·4	20·6
,, ,, gas burned	53·4	56·4	59·8	51·5	55·9	56·4	57·6	52·3	52·9	54·4	51·5
Gas per indicated H-P. H. (litres)	735	680	725	668	665	694	687	700	677	703	—
,, effective ,, ,,	851	835	892	835	832	850	825	822	850	853	946

covers the igniting flame, and the cycle is again completed.

The improvements made in the Otto gas engine by the well-known firm of Crossley Brothers are, as their continued use of the Otto patent shows, not so much changes in principle, as furtherance of the easy and practical action of the engine by overcoming mechanical difficulties. We shall deal with some of these improvements, but from the limited nature of this work only briefly, when considering the various organs of the gas engines and their improvements *en resumé*.

Other Engines of this Type.

Belonging to this class of engine is the later form of **Lenoir** (which to prevent misconception we described at an earlier part of this book).

C. G. Beechey (patent No. 1,318, of 1882) has introduced an engine in which it is endeavoured entirely to remove the products of combustion, after each explosion and to regulate the working by determining a partial vacuum behind the piston.

J. Shaw (patent No. 5,178, of 1881) and **C. Wilden King** (patent No. 4,223, of 1881) provide the combustion-chamber with walls of refractory clay.

Martini (patent No. 1,060, of 1883) endeavours in compression motors to better utilise the expansion of the explosive mixture, by so arranging that the drawing in and compression of the explosive mixture is produced by a short portion of the engine stroke, whilst expansion and the exhaust are accomplished during a longer portion of the stroke.

In **Wordsworth & Lindley's** engine the cycle is characterised by the introduction of a lost stroke of the pump compressing the charge in the motor-cylinder to a much greater tension.

Amongst the other English patents, that it is beyond our scope to describe in detail, can be mentioned, as including improvements in this class of engine, those of **Bickerton** (1,363, of 1881); **Clayton** (4,075, of 1881); **Fielding** (532, of 1881); **Fiddes** (5,219, of 1880); **Hutchinson** (5,471, of 1880); **R. Hallewell** (5,092, of 1878); **Jenner** (3,607, of 1880); **Linford** (1,500, of 1879; 2,990, of 1881); **Sumner** (1,360, of 1882); and **Watson** (5,052, of 1879).

CHAPTER III.

COMPRESSION ENGINES WITH COMPRESSING PUMP.

Wittig and Hee's Engine.

THIS engine is essentially distinct from the previous class, by the fact that instead of one cylinder serving alternately as working cylinder and pump, it has two, each performing only one of these two functions. The engine is vertical, the two cylinders A pump, B working, Fig. 42–45, are placed in a cooling-jacket C with which they form one casting; the shaft D is above the cylinder and the bearings are an expansion of the jacket, serving generally as a frame. It has two cranks, both standing in unison so that the pistons make stroke together. The latter F and E are constructed as plunger piston and so arranged that in the working cylinder a considerable combustion space obtains, about five eighths of the piston stroke. Both cylinders are connected together by an outside pipe; in this is interposed an automatic back stroke valve, kept closed by a spring. The engine works in the following manner: if the pump-piston is on the out-stroke from it lowest dead point, then it draws in the fresh combustible mixture, if on the instroke then it compresses the mixture. As soon as the tension is sufficiently high, it enters, through the back-stroke valve, into [illegible] ing cylinder, where it mixes with the remnant combustible products. If the pistons stand at the lower dead point, ignition follows, and the explosion closes the back-stroke valve, and the combustible products expand in the working cylinder, driving the piston up. On the in-stroke the piston presses the combustion products out of the engine. After it has performed about three fifths of its stroke, it closes the outlet and the remaining combustion residuum is compressed. Immediately afterwards, the back-stroke valve opens, and the fresh mixture enters, as already stated, from the pump, so that during the last part of the revolution both cylinders communicate, the contents of both cylinders mix in the working cylinder and are pressed together in common by both cylinders.

The essential details are the following. The air enters the engine at *a*, the gas at *b* by a regulating valve *v*; the access is regulated by the inlet valve *c*.

This is opened by an eccentric from the shaft; it is usually closed by spring pressure and only opens when the eccentric, by means of the catch *e*, presses the spring together. The pipe *f* leads from the pump into the working cylinder; in it is intercalated the back stroke, valve *g*. This pipe opens into a slide box, the slide of which operates the ignition, through the conduit *h*; this slide box is in connection with the interior of the cylinder. The outlet is regulated by the valve *i*, generally held closed by spring pressure; it is governed by the shaft, and opened at the proper time by a cam on the shaft. The ignition G has the following arrangement, (see also Fig. 46). In the slide cover a flame, *l*, burns; in the slide itself the chamber *m* is shut. If the slide stands in its lower dead point, then the combustible mixture flows through the small conduit *n* of the slide box into the chamber *m*, whilst through *o* air can enter. This mixture is ignited at the flame at the slide cover. If the slide is on the out-stroke, then the chamber *m* cuts off the connection towards *l* and *o*; there burns in it, therefore, a mediating flame, which strikes into the slide box and causes an explosion so soon as the chamber communicates with the conduit *h*. In order, however, that the mediating flame should not be extinguished during the back stroke, the feed follows continuously through *n*. For this object *n* opens into the trough *p* sunk into the valve face, the trough communicating with the bore *q* of the slide. However, in order to regulate the feed sufficiently and give the mediating flame the direction of the conduit *h*, there are two pins, *r* and *s*, standing opposite to each other. The first is hollow and serves only as continuation of the bore *q*; the other is conical in front and can be more or less moved forward, so that therefore the opening of the first pin out of which the feed gas streams is more or less closed. The regulating is done by a conic-regulator. In the older constructions this closed more or less a valve in the gas pipe; it was also so sensitive that it almost always found itself in its extreme positions, that is, the valve was held quite closed or entirely open, yet the arrangement for the attainment of a mixture always equally combined was less suitable than that of Otto's. On that account the latter arrangement is imitated in the newest engines of this system.

The regulation valve *v*, usually held closed by spring pressure is, with normal action, opened with the entrance valve *c*, usually by the cam; if the engine however, goes too quickly, the regulator presses the upper rotary part *x* of the valve bar, and *i*, the catch consequently does not hit it, and the valve remains closed. The engine thus receives either no gas at all or a full load.

That this construction, compared with Otto's, is a progress there is no doubt. The engine described, particularly with no load, is not quite so regular and uses somewhat more gas.

Körting - Lieckfield's Engine. This construction designed by Messrs. Körting, of Hanover, follows very closely the previous one, and is only essentially different in the ignition and regulating. We have here also vertical cylinders, one serving as pump, the other as working cylinder. Air and gas enter through a mixture valve, into the first, and are here compressed. The manner of working is essentially the same as previously explained. As concerns the ignition, the very simple arrangement is shown in Fig. 47. *a* is a hollow pin and below at its point at *b* is drilled a fine opening; at *c* and *d* a ring of openings. This hollow pin is moved in the socket *e* attached to the working cylinder, so that the point *b* rises in the feed conduit. The socket has corresponding openings before which the ignition flame burns. If the pin *a* stands in the position shown, it will be filled with combustible mixture during the feed period: if it, however, rises then, the mixture contained in it is ignited; so soon as it is free from the cam action, it is caused by a spring (not shown) to resume its first position, and causes the explosion through the burning mediating-flame contained in it. During the rebound the tension is equalised through the opening *c*. The arrangement is essentially more simple than the slider of Wittig and Hee, and works with perfect certainty and more regularly.

The second essential peculiarity is the regulation: it is based upon the idea of altering the tension of compression of the mixture. This takes place through increase of the compression space of the pump. To this end, there is provided next to the pump, a hollow space, and this is placed in connection with it by a conduit. This conduit is opened by the regulator when the engine goes too quickly. When the engine exceeds its usual velocity, the feed mixture is given less tension in the working cylinder, and therefore the working force is a little less until the regulator closes the connection between pump and hollow space. The idea, the basis of this arrangement is a good one; the same end is attained here as in the Otto regulation; namely equal combination of the mixture. On the other hand the ngine receives a weaker propulsion at each revolution, whilst with Otto's, so long as the regulator holds the gas valve closed, the engine experiences no propulsion at all. It would appear that the described arrangement in reference to the regularity of action must be more favourable than that of Otto. Whether the practical result realises the object sought can only be decided by comparative experiments, which at the present time are not before us.

Simon's Engine.

This is a steam-gas engine and appeared first at the Paris International Exhibition as an invention of Simon, of Nottingham. Fig. 48 representing it, embodies a somewhat later construction; however, it will serve only as an explanation of the idea; the engine is now built horizontally.

A is the pump and B the working cylinder. The first draws in the mixture through a valve, *a*, compresses it, and repasses it through the valve *b*, into the reservoir C. From this it reaches, by means of the slide *c*, into the working cylinder. In this a constant flame, *d*, burns in front of a wire net, which is to prevent the return stroke into the reservoir, and so operates that the mixture in the mass is ignited as it overflows. After a sufficient quantity of it has entered, the slide closes the inlet conduit, and the combustion products expand until the end of the piston lift. In the back action they are driven out by means of the slide d', into the open air through the worm *e*.

This worm lies in a small boiler D. The combustion products, still very hot, evaporate the water, and the steam generated is conducted through the pipe *f*, controlled by means of the slide *c*, into the water cylinder, where it comes to the help of the gas mixture, and lightens the oiling.

The regulation is effected through simultaneous partial cutting off of the entrance of gas and air, in a perfectly rational manner, by means of the slide *g*, which is moved by the hub of the regulator, formed to correspond, against which it bears by the operation of a spring.

It is observable that it is essentially distinct in two points from the arrangement previously described, namely by the gradual consumption instead of explosion and by the steam effect.

The employment of steam is not new. Hugon applied it when he injected water into the cylinder. He desired, thereby, to increase the output and diminish the oiling, an attempt entitled to praise. The expenditure of steam, instead of water, appears rational, because thereby the heat is partially regained, regenerated by the combustion products. It may be asked, however, whether it should be regarded as an appropriate object for the gas engine which has the direct aim to put aside the steam boiler, with all its evil accessories and dangers, again to resuscitate them. That the small industries would like to be occupied with it, cannot be assumed. It also must not be forgotten that the attendance is essentially heavier, and the engine, as a whole, is considerably more complicated than with a mere gas engine. If, consequently, the first peculiarity of the Simon engine appears of questionable value, this cannot be said of the second. The introduction of the gradual combustion in place of the explosion, is doubtless a progresive principle; there is only the question of carrying out the end suitably. Already Otto works by the introduction of after combustion upon the idea of gradual combustion; and Simon's arrangement is nothing but the consequence of this. The more gradually the heat is introduced so much more time and opportunity has it to change into work, and so much less of it is turned into useless effect in the cooler. That we may do work with much less initial tension is not of much importance, but as a help, not to be despised. According to what has been brought forward, it is not without reason to regard the Simon engine as valuable in the future; the question only is whether the difficulties to develop the idea are to be overcome and whether, perhaps, there may not be other unfavourable working conditions. This can only be determined by many experiments, which, in the interest of small industries, we wish all success.

Dugald Clerk's Engine.

To this time the best-known engine of the type represented by this sub-division of compression motors is perhaps that of Dugald Clerk. We shall first describe this engine and then, in as nearly as possible the inventor's own words, discuss the views that led him to the design. Subsequently in another chapter we shall give the somewhat opposed views of M. Witz, as to the most economical action of a gas engine. It must be borne in mind that we endorse the views of neither the one nor the other. Although this subject is by no means a new one, yet the theory has to be established and at this stage the honest writer can do no more than present equally the arguments advanced.

The cycle of this engine is as follows, for one turn of the shaft. As regards, first, the pump cylinder, the crank of this cylinder is set on the shaft 90° in advance of the driving crank. The pump, during the course of the out-stroke of its piston, draws in the volume of explosive mixture of air and gas necessary to actuate the out-stroke of the driving cylinder; and an equal volume of air is drawn in that is not to mix with the explosive mixture at all. During the in-stroke, there is expelled, first, the air not mixed with the explosive mixture; second, the combustible products remaining unexploded.

During the out-stroke of the driving cylinder there occurs the explosion of the compressed mixture under nearly constant volume; the expansion; exhaust of the products of combustion. During the in-stroke, there occurs the ends of the exhaust, and the clearance of the cylinder by air from the "displacer," the piston of which is at the middle of its back-stroke when that of the driving cylinder is commencing its stroke. The exhaust is then closed, and compression of the mixture takes place in the motor cylinder and in the explosion chamber, during the first half of the back-stroke, by the displacer.

The distribution of the air and gas mixture has to be considered from two points of view as occurring in the pump cylinder and also as occurring in the motor cylinder.

In the pump cylinder, during the outstroke, aspiration occurs, (1) of the mixture, (2) of the air juxtaposed to the mixture.

> (1). The gas is drawn in by the tube *g* (Fig. 49.), through the lighting chamber *j*, the conduit *g*, the valve *m*, and the tube *p'*. The air mixes with the gas around the valve *m*, arriving at *p'*, perfectly mixed. The mixture enters the displacer cylinder by an annular orifice *p''*.
>
> (2). The aspiration of the air to be superposed upon the mixture, occurs towards the middle of the out-stroke of the displacer piston, and at the commencement of that of the motor piston, when the slide closes the orifice *g'*, and the aspiration of the gas. Air alone is then drawn in.

During the in-stroke of the pump piston, the motor cylinder is cleared, of (1) the air juxtaposed on the mixture during the first half of the back-stroke of the displacer piston and during the second half of the out-stroke of the motor cylinder, through the tube *p'*, valve A, and light chamber *l'*, into the combustion chamber of the motor cylinder. This air clears before it the products of combustion. (2) Of the explosive mixture by the same way as the air, during the second part of the back-stroke of the displacer piston and the first part of the back-stroke of the motor piston.

In the motor cylinder the following takes place :—

(1). On the out-stroke—lighting, explosion of the mixture, compressed in the explosion chamber and preceded by a thin layer of pure air, or at least by a layer of air poor in gas. Expansion. Exhaust by the openings *e*, uncovered by the piston towards the end of its stroke. Admission of air from the displacer by A.

(2). On the in-stroke—end of the exhaust and the clearance of the products of combustion by the air of the displacer. At midstroke, all the mixture is admitted into the explosion chamber and into the cylinder. Compression of the mixture, the valve A being closed.

For the regulation of the admission of gas to the conduit *g'*, a spring bar is connected by a tappet to the slide, by which it is guided.

The ignition is effected, by the carrying in the slide, of a flame under pressure. The passage *l'*, communicates with the base of the combustion chamber, and receives the explosive mixture by the openings and conduits to be found in the Figs. 49 and 50.

Details as to the working pressures and temperatures of this engine will be found described in the chapter devoted to the inventor's theory of the gas-engine.

Other Engines of this Type.

In **Livesay's** engine (patent No. 117, of 1880, and No. 2,299, of 1880) the compression reservoir has no piston for compression purposes.

In **Turner's** engine (patent No. 3,182, of 1880, and No. 362 of 1882) of this type also, the compression cylinder is dispensed with by different arrangement of the two cylinders which are alternately motor and auxiliary cylinders.

Besides other engines, **James Atkinson** has introduced a three-cylinder engine, the front face of the piston of which compresses the detonating mixture into a tube reservoir, small enough to avoid danger of explosion and to be sensitive to the action of a regulator. The mixture compressed at the front faces of the pistons, which run parallel, is distributed to the rear of the pistons by a circular slide valve.

All of Atkinson's motors present novelties of ignition, regulation, and distribution, that we regret it is beyond the scope of this work to consider. The patents are Nos. 4,086, of 1881 ; 4,378, of 1882; and 4,388, of 1882.

In **Robson's** engine (patent No. 645, of 1883), and in that of **C. H. Andrew** (patent No. 3,066 of 1883) the piston rod has a piston at each end, respectively working pump or motor piston.

Maxim's engine (Figs. 51 to 54, No. 132, of 1883), presents many novelties, both as regards its cycle and details.

The operation of the engine is as follows:—A suitable pipe for the supply of gas being connected to the pipe O and to the burner *g* the machine is turned one revolution by hand; the air is compressed in the chamber U, and the air and gas mixed in the chamber *a* enter equally in such a manner that there will be in the space U a pressure of gas and air of about 4·20 kilogrammes per square centimetre. As the machine continues to turn, and the piston approaches the end of its stroke, the slide-valve L is moved by the eccentric into such a position that the flame enters at K and causes the explosion of the charge. The explosion impels the piston forward, and at the same time compresses the air on the opposite side of the piston (Fig. 52) into the chamber S. When the piston is about 25 millimetres from the other end of its stroke, the head of the rod comes in contact with the small lever G, and thereby opens the large exhaust valve which permits the residues of the explosion of gas and air to escape. As the piston continues its forward movement, it passes the apertures T, and the air which has been compressed into the space S passes through these apertures and forces out of the cylinder, by the exhaust pipe, all the gaseous products of the explosion, and fills the cylinder with pure air. The expansion of the air by the heat sufficiently augments its volume, not only to expel the gas residues, but also to cause a certain quantity of pure air to flow through the exhaust aperture. On its return stroke, the piston passes the holes T, draws in a fresh charge of air by the apertures R, and when it has closed the holes T, the exhaust-valve D is closed; at this moment the cam W is in contact with the friction roller X, the piston of the gas pump is impelled rapidly forward, and the contents of the chamber *a* are forced into the cylinder. The piston B returning in the cylinder compresses the air and gas in the chamber U, and the flame being brought into contact with the gas, the charge is exploded and the piston performs its forward stroke as before. The piston of the gas pump is caused to perform its outward stroke by the action of the spiral spring *b*, which holds the friction roller X against the cam. When, moreover, the engine is working slowly and the cam occupies on the shaft such a position that it is brought in contact with the friction roller X, the piston of the pump is returned suddenly to the bottom of its cylinder at each return stroke of the machine. But whenever the speed of the machine becomes sufficiently great for the centrifugal force of the weights to move the spring *i* outward, the cam W comes into such a position that it no longer touches the roller X; this position is represented in Fig. 51. When the speed diminishes, the spring *i* by its pressure upon the lever *l*, forces the pin *p* inward and cau the cam to slide upon the shaft until it comes in tact with the roller X; a fresh charge of gas will t be forced into the cylinder.

In a gas-engine, it is necessary, in order that no gas shall be lost, to regulate the machine rather by the number of the explosions than by their force, because a less proportion of gas would not produce an explosion. The proportion of air to gas should be about ten to one. This quantity may, moreover, be varied from five to fifteen, and if it is desired to obtain great regularity of the motor, the cam W may be made of different layers or plates, so that while doing less work the machine may be supplied with less gas. The capacity of the cylinder *a* is, moreover, considerably greater than is necessary whatever be the amount of gas employed; so that there is a margin for the regulation of the machine. The cylinder of the pump will be entirely filled at each stroke, but the entrance of gas can be regulated by means of a cock, having an index, fixed on the pipe O. It is obvious that, with a copious supply and a great pressure of gas in O, the air valve P would not open, and that the cylinder of the pump would be filled with gas only, at each stroke. If, moreover, the cock at O were partially closed, the gas could not enter rapidly enough to fill the cylinder when the movement of the piston was effected rapidly in such a manner that it would produce a sufficient suction to open the valve 7 which closes the air passage P. If air equal to half the amount of the charge is sufficient to produce the maximum explosive effect, then the cock at O should be sufficiently closed to allow the half of the contents of the pump to be drawn in at P. In Fig. 54 it will be observed that there are two valves placed one above the other, and that in every case the aspiration causes the raising of the valve 6 and the valve 7, if O is closed, but not if O is open. The mixture of air and gas will be more effectual if a small quantity of air is mixed with the gas before it arrives in the exploding cylinder.

When the piston moves forward and passes the holes T the air which has been compressed in S passes into the cylinder, as above stated. As soon as the piston has passed these holes on its return stroke, the compression commences in the cylinder. At the same moment the gas and air are forced in at the other end of the cylinder, and before the gas and air have time to become intimately mixed, they are compressed and ignited. At the moment of the explosion there is a layer of compressed gas and air at the left-hand end of the space U (Fig. 52), and a layer of pure air against the piston B; the explosion at the left-hand end forces the air towards the right, and produces a high pressure with a much smaller consumption of gas than if the gas were mixed with the whole volume of air, because gas which would produce an explosion while occupying only one-third of the space U, would not explode if mixed with the whole of the air contained in the cylinder. Great economy is thus effected. By completely surrounding the cylinder by the air space S, a large number of holes T may be made, so that the residues of the gas may be completely expelled from the cylinder whilst the motor performs one-twelfth part of its stroke. By giving to the connecting rod a relatively small length, the time occupied by the piston for its return stroke is augmented so that the exhaust valve remains open during a considerable time, whilst the machine only makes one-twelfth of a stroke; the time during which air may enter is augmented accordingly. The forward stroke of the machine is also rendered more rapid by the employment of a short connecting rod in such a manner that the piston moves rapidly, and does its work before the gas can cool and diminish its pressure. The air necessary for expelling the foul gases from the cylinder is drawn in by the apertures R. These apertures are closed by clack valves of ordinary construction, opening freely inwards, but preventing any egress of air. The space S is of such size that the pressure at the end of the stroke will not exceed 0·350 kilogramme per square centimetre. The water casing is not cast with the cylinder A. The joint which connects them is slightly conical, in order to ensure its being tight. The rocking shaft *m* is forged in one piece with the arms 8, and is held against its bearing by the action of the spring *h*. If during the working of the machine, the governor forces the cam W inward, and it comes in front of the roller X, this spring yields and the shaft *m* is forced inward, so that when the cam has passed the roller X, the spring forces back the shaft and causes the roller to engage with the cam W.

It will be seen that when the machine is not charged, or is working lightly, the action of the governor will cause the said machine to lose a stroke, that is to say, to make one stroke without effecting any work. The gas not entering, no explosion will occur.

The flame which causes the explosion of the charge is admitted to the cylinder in the following manner:—The action of the eccentric moves the slide-valve L forward until the space M (Fig. 53) coincides with the aperture *f*. The draught of the chimney then draws in air at *f* whilst discharging at M all the gases which have been exploded.

The lower extremity of the chimney is reduced in diameter to produce a draught at this point. When the chamber M coincides with the aperture *f*, a part of the gas contained in the chamber M is drawn into the chimney; this portion of the gas is ignited, and the eccentric pushes back the slide-valve and closes the aperture *f*. In order to ensure that the gas in the chamber M shall not be extinguished, the chamber *d* is employed, which not only supplies gas to M, but augments the pressure at this point in such a manner that when it is opened to K the flow of the gas is not so rapid as it would otherwise be.

There is a small hole *c* through the slide-valve L, and another hole *e*, and the space between these holes is a little greater than the hole communicating with the chamber *d*. When the hole *c* passes *d*, the explos
gas flows through *c* and fills *d* with gas at the sa

pressure as that in K. When the slide-valve is moved forward it closes *c* and opens *e*, the gas compressed into *d* then enters through the port *e* into M, and as it is of an explosive nature, it does not require oxygen to be supplied to the flame; before this flame is extinguished, the slide-valve L moves forward until M is in communication with K, and the explosive gas entering is ignited and the explosion occurs. If necessary, a small groove may be cut in the slide-valve L, so that a small quantity of gas may escape from K into M, whilst M is in communication with *f* and the chimney.

Oil may be supplied to the cylinder with the gas and air through the admission valve I. The oil-cup may be of the kind usually employed in steam engines, and may be connected with the passage between 6 and 1. The metal tube 2 is rendered tight at its extremities by means of screw-nuts. The long screw-thread at one of its extremities permits of its insertion.

The spiral spring should have considerable elastic force, and should be compressed by the screw so that a pressure of about 6·30 kilogrammes in S will be necessary to open the valve. The object of employing a safety valve upon this engine is to prevent too great pressure in the cylinder, in case an accidental explosion in the cylinder should take place whilst the charge is being compressed and the piston is moving against the charge, instead of in the other direction.

The standards are of cast iron and are provided with bearings of anti-frictional metal; the admission valve

I has a long rod which extends through the bottom of the cylinder; this valve is kept closed by a spiral spring *k*. Leakage around the rod of this valve is prevented by means of a cap which completely encloses the spring and the valve.

Brass should not be employed for the heated parts of an engine, they should either be made of cast iron or of steel, the double stop valve should, however, be of brass. The friction roller should be of steel connected to the arm by means of a steel pin, and the arm should be firmly keyed to the rocking shaft *m*. The spring F should be of considerably less strength than the spring E in order to allow the valve D to be closed.

The gas engine of **C. W. Siemens** is distinguished by the employment of a regenerator or economiser of heat, also of a differential piston, and of a method of ignition permitting of working with gas mixtures of lower inflammability and less richness than possessed by ordinary detonation mixtures.

In the specification of a previous patent to which we shall presently refer, No. 2,504 of 1881, C. W. Siemens described a form of gas motor engine in which a shielded differential piston forces by its down-stroke a combustible mixture of gas and air into a receptacle, whilst a charge of the mixture from the receptacle enters the cylinder above the piston and is ignited and burns therein, expanding in volume. A later invention relates to means of ensuring the ignition of the gaseous charge, particularly when a mixture of low combustibility is employed, and to a modified form of engine in which, instead of a gaseous combustible mixture, air is employed, either with a slight admixture of combustible gas or water vapour or without such admixture.

For the purpose of ensuring ignition of the gaseous mixture entering the cylinder, a portion of the entering charge is caused to become enriched by the addition to it of combustible gas or vapour unmixed or partially unmixed with air, so that this portion of the charge is readily ignited, and communicates ignition to the rest of the charge which is less rich in combustible matter. According to one method is provided a cock or revolving slide moving in time with the engine shaft; a cavity in this cock or slide at one part of its revolution receives a supply of combustible hydrocarbon liquid, preferably of a volatile kind, from a supply vessel connected to the cock or slide by a pipe. At another part of the revolution of the cock or slide, that is to say, at the time when the charge begins to enter the cylinder, the liquid contained in the cavity is presented to a current of a portion of the gaseous mixture or air on its way to the cylinder and mixes therewith, enriching it; and this enriched current then passing electrodes furnishing a spark, or a platinum wire rendered incandescent by an electrical current, becomes ignited, and ignites the remainder of the charge, which passes separately into the cylinder heated by its passage through the regenerator

A vessel containing a supply of hydrocarbon oil preferably of volatile character, is raised above the engine, and from this vessel, pipes lead to two cocks, one for each cylinder, these cocks being caused to revolve in time with the engine shaft by a chain communicating motion from a chain wheel on the engine shaft to a chain wheel of equal size on the spindle of the two cocks. The plug of each cock has on its side a small hollow, which during one part of its revolution presents itself under the oil pipe and receives a charge of oil; during another part of its revolution, which is timed to correspond with the flow of gaseous mixture to the cylinder, the hollow of the plug presents itself to the bend of a pipe leading from the top of the cylinder to a port opening in the cylinder below the regenerator, in which port are situated two platinum wires. These wires are connected with the brushes of a commutator on the engine shaft, which commutator is in electrical connection with the poles of a battery, dynamo-electric machine, or other source of electricity. Instead of two wires to produce a spark, a single wire may be arranged to be kept incandescent, or to become incandescent at the proper time for ignition.

According to another method, there is worked from the piston of the engine the plunger of a pump, which forces combustible gas unmixed with air into a receptacle; a portion of this gas is caused to enter the cylinder along with a portion of the mixture of gas and air, enriching it, so that it is ignited as above described. The gas pump may have its suction and delivery governed by the same revolving slide as that which governs the supply and discharge of the engine, and the passage of gas from the receptacle of the pump to join the current of gaseous mixture entering the cylinder is governed by a valve which is opened by the pressure of the entering current acting in opposition to a spring on a piston connected to the stem of the gas valve.

In the modified forms of engine, heat is imparted to currents entering the cylinder by a regenerator supplemented by jets of combustible gas or vapour which may be previously heated, and which intermingle within the cylinder with the current of compressed air heated by its passage through the regenerator. Or according to another arrangement, the compressed air on issuing from the regenerator is further heated by one or more jet furnaces of the following kind:—In the upper part of the cylinder is a deep cup projecting down into the cylinder, in this cup is burnt a gas flame. The products of combustion ascend an outer pipe heating the air supply pipe on their way to a chimney. Surrounding the cup and supported on a grating made in one piece with the cup, which is preferably made of copper or other well-conducting metal, is arranged an annular regenerator, the lower part of which is thus heated by conduction. The engine operates as follows:—The annular piston in its up-stroke draws in air alone, which in its down-stroke it delivers into the receptacle. A charge of air from the receptacle is admitted to the top of the cylinder, and, entering it through the regenerator, is heated in its passage, and becomes still further heated by contact with the heated cup, thus expanding in volume and propelling the piston downwards. By the up-stroke of the piston the air which had performed work is expelled through the regenerator, giving up in its passage a large portion of its heat, which is available for heating the succeeding charge of air entering the cylinder through the regenerator. The air thus discharged operates as a blast in the chimney, thus causing a draught, by which the combustion in the cup is rendered more active. For engines of small size a single cup with its gas and air supply pipes suffices, but when the cylinder of the engine is of considerable size, instead of a single cup with its adjuncts, several cups are employed, thus subdividing and enlarging the heating surface.

The arrangements described for heating the cylinder charge in and after its passage through the regenerator are obviously applicable in engines of other forms.

The latest engine designed by Sir C. W. Siemens, is more notable for its theoretically perfect plan than for any practical results that have as yet been attained by it. It is very simple and should be productive of highly efficient results, but it is observable that the highest results have not always followed the best theoretical design, particularly in gas-engines.

The engine comprises two motor pistons, the cranks of which are set at 180°. Distribution is effected by a single hollow slide, revolving synchronously with the motor shaft.

The cycle of these cylinders is the following:—During the out-stroke the piston aspires the detonating mixture at the same time that it clears out, by its outer face, the products of its preceding explosion through a regenerator, and finally into the exhaust. During the in-stroke the piston clears out by its interior face the mixture drawn at the preceding stroke through the slide. Thence the compressed mixture passes to the compression reservoirs. At the same time the outer face of the piston receives through the regenerator the compressed mixture which is ignited, and exerts an effect proportional to the difference of the two faces of the piston. Each of the pistons gives an explosion per revolution. The ignition is effected by the action of an electric spark on a very inflammable mixture, obtained, as previously described, by the use of liquid hydrocarbons.

Sir C. W. Siemens, in a discussion on a paper read by Mr. Dugald Clerk on the "Theory of the Gas-Engine," before the Institution of Civil Engineers, has said, "he had from time to time given a great amount of consideration to the action of negative combustion or dissociation. It was well known that by combustion no unlimited degree of temperature could be attained. Thus, in a furnace worked at very high temperature the fuel was not completely burned when it came in contact with the oxygen of the heated or non-heated air.

The moment a certain comparatively high temperature was reached the carbon refused to take up oxygen, or the hydrogen refused to take oxygen, and what had been called by Bunsen and, shortly after by St. Claire Deville, dissociation arose. The point of dissociation was not a fixed one; partial dissociation came into play at a comparatively low temperature, and went on increasing at a high temperature in very much the same ratio as vapour density increased with temperature. Thus, if aqueous vapour were passed through a tube at a sufficient temperature the whole of the vapour would be separated. It might be that the determinations of St. Claire Deville were not quite correct, but in the meantime they might be regarded as being so. He found that at atmospheric pressure the point of half dissociation of aqueous vapour arose at a temperature of 2,800° Centigrade, and that of complete dissociation at a much higher temperature. Taking that law as determined by the French philosopher, it did seem reasonable to suppose that when a mixture of hydrogen and oxygen, with or without a mixture of nitrogen, exploded, the point was reached beyond which the temperature did not increase, and that point was 1,500° Centigrade. If such a temperature was reached in the working cylinder complete combustion would not take place immediately, but only partial combustion would occur, which would go on as the temperature diminished by absorption into the cylinder or by expansion, and that combustion would be completed only in the course of the stroke. With reference to the early engine which was constructed in 1860, it combined other elements, which were entirely wanting in the gas engines of the present day, and taking either of the three types, it was, in his opinion, in the condition of the steam engine at the time of Newcomen. The fuel was burnt in a cylinder which it was attempted to keep cold by passing water over it, and it was easy to see that the heat so generated, was only partly utilised for maintaining the state of expansion of the heated gases, the cold sides of the cylinder taking a good half of it away at once, thus causing a great loss. Then, there was another palpable loss in these engines. After expansion had taken place, after half the heat had been wasted in heating a cylinder which was intended to be kept cool in order to allow the piston to move, the gases were discharged at a temperature of 1,000°, or in the best types about 700°. That amount of heat, representing in one case one-half and in the other two-thirds of the total generated, was thrown away. This was heat which could be saved and made useful. Instead of commencing the combustion at a temperature of 60°, if the heat of the outgoing gases were transferred to the incoming gases, combustion might commence at a temperature of nearly 1,000°, and the result would be a very great economy. In the engine which he constructed in 1860 all those points were fully taken into account. The combustion of the gases took place in a cylinder without working a piston, and in a cylinder that could be maintained hot, and the gases, after having complete expansive action, communicated their heat by means of a regenerator to the incoming gases before explosion took place. Although the engine was not worked with ordinary gas used for illumination, but by a cheaper kind made in a gas producer, he then thought that a gas engine constructed on that principle would prove to be the nearest approach to the theoretical limits which could never be exceeded, but which might exceed the limits of the steam engine four or five fold. The engine promises to give very good results."

The great advantages afforded by the cycle of this class of engines have led many inventors into the field; we give here the chief English patents, in the order of their date.

G. W. Weatherhogg, 3972, of 1878. **Mills and Haley**, 5052, of 1879. **H. Robinson**, 117, of 1880. **J. R. Pursell**, 3869, of 1810. **C. Beechy**, 4270, of 1880. **K. Rider**, 4419, of 1880. **E. Edwards**, 1765, of 1881. **L. H. Lucas**, 3527, of 1881. **J. Butcher**, 3786, of 1881; 1835, of 1883. **W. Watson**, 4608, of 1881; 6214, of 1882. **C. Tonkin**, 5201, of 1881. **H. Williams**, 5456, of 1881. **C. Emmet**, 397, of 1882. **Haigh and Nuttall**, 614, of 1882; 2517, of 1883. **Wordsworth and Lindley**, 703, of 1882. **J. Fielding**, 994, of 1882; 3070, of 1883. **Drake and Muirhead**, 1717, of 1882. **Worsam**, 2126, of 1882. **C. Beissel**, 3435, of 1882. **J. Woodhead**, 21, of 1883. **W. Hale**, 2192, of 1883. **De Kabath,** 999, of 1883. **D. Nile,** 3135, of 1883. **H. Bull,** 5113, of 1883. **Pickering and Hopkins,** 5406, of 1883. **Griffin,** 4080, of 1883.

COMPOUND ENGINES.

The application of the principle of successive expansions of the active fluid in steam engines presents so many economical advantages as to have led inventors to seek similar advantages in the case of the gas engine. But the analogy is scarcely practical, because of the greater loss by radiation in the case of the gas engine.

Otto's Compound Gas Engine is compounded by the addition of an expansion cylinder to the inventor's double cylinder engine. The patent is No. 245, of 1879.

Other engines of this type have also been patented by **D. Clerk,** No. 4948, of 1882; **P. Niel,** No 1026, of 1882; **Wordsworth and Lindley,** No 3568, of 1883.

PART III.

CHAPTER IV.

THEORY OF THE GAS ENGINE.

In the previous part of this work we have described the different forms of gas engines, and dealt with them from the mechanician's standpoint; we now come to consider the nature of the working fluid, its physical and chemical changes and its thermodynamic relations.

The working fluid consists of a mixture of inflammable gas and air, generally the ordinary illuminating gas is employed; but in works where large quantities of gas are required as a motive power, an atmospheric or non-illuminating gas, such as that made in a Dowson gas producer, is manufactured for the purpose.

The composition of ordinary gas varies in different places, and with the description of coal used in its manufacture. We give the following analyses :—The first of Manchester gas by Bunsen and Roscoe; the second is the mean of several analyses, by Humpidge, of London gas.

Volumes.	(1)	(2)
Hydrogen (H)...	45·58	47·83
Marsh Gas (CH_4)	34·90	36·94
Carbonic Oxide (CO)	6·64	5·27
Ethylene (C_2H_4)	4·08	7·02
Butylene (C_4H_8)	2·38	
Sulphuretted Hydrogen (SH_2)...	·29	—
Nitrogen	2·46	5·29
Carbonic Acid	3·67	—
Oxygen (O)	—	·56
	100	104·91

In the second case the extra volumes are due to all the heavier hydrocarbons $C_n H_{2n}$ being reckoned in the form of ethylene.

Glasgow and Edinburgh gases are richer in the heavier hydrocarbons, and consequently per cubic foot yield more heat on combustion.

We proceed to calculate the heat evolved from the Manchester gas. The calculations are more readily effected in the decimal system; we shall afterwards give reduction factors, where necessary, to convert the results into the irrational system still in use by English engineers.

Taking one hundred litres, as the volume of gas employed, we find the weights in grains, to be as follows:—

	Vols.		Weight of 1 Litre.				Grms. per 100 Litres.
H	45·58	×	·0896	×	1	=	4·08
CH_4	34·90	×	·0896	×	8	=	25·02

	Vols.		Weight of 1 Litre.				Grms. per 100 Litres.
CO	6·64	×	·0896	×	14	=	8·33
C_2H_4	4·08	×	·0896	×	14	=	5·12
C_4H_8	2·38	×	·0896	×	28	=	5·97
SH_2	·29	×	·0896	×	17	=	0·44
N	2·46	×	·0896	×	14	=	3·08
CO_2	3·67	×	·0896	×	22	=	7·24

The amount of oxygen just theoretically necessary for the complete combustion of the one hundred litres may be found from the following chemical equations.

O_2	+	$2\ H_2$	=	$2\ OH_2$				
2 vols.		4 vols.		4 vols.				
$2\ O_2$	+	CH_4	=	$2\ OH_2$	+	CO_2		
4 vols.		2 vols.		4 vols.		2 vols.		
O_2	+	$2\ CO$	=			$2\ CO_2$		
2 vols.		4 vols.				4 vols.		
$3\ O_2$	+	C_2H_4	=	$2\ OH_2$	+	$2\ CO_2$		
6 vols.		2 vols.		4 vols.		4 vols.		
$6\ O_2$	+	C_4H_8	=	$4\ OH_2$	+	$4\ CO_2$		
12 vols.		2 vols.		8 vols.		8 vols.		
$3\ O_2$	+	$2\ SH_2$	=	$2\ OH_2$			+	$2\ SO_2$
6 vols.		4 vols.		4 vols.				4 vols.

Whence we find that the

		Litres of O.			Litres.	
					OH_2	CO_2
H	will require	22·79	producing on combustion		45·58	—
CH_4	„	69·80	„	„	79·80	34·90
CO	„	3·32	„	„	—	6·64
C_2H_4	„	12·24	„	„	8·16	8·16
C_4H_8	„	14·28	„	„	9·52	9·52
SH_2	„	·44	previous		—	3·67
100 Litres.		122·87			143·06	62·89

The number of units of heat reckoned in gramme-degrees C, evolved by the complete oxidation of the coal gas constituents is as follows :—

			Heat in water-gramme-degrees.
One gramme of	H	evolves	34·180
„ „	CH_4	„	13·100
„ „	C_2H_4	„	11·900
„ „	C_4H_8	„	11·400
„ „	CO	„	2·400

Whence we obtain from the

					Gramme degrees.
H	4·08	×	34·180	=	139·454
CH_4	25·02	×	13·100	=	327·762
CO	8·33	×	2·400	=	19·992
C_2H_4	5·12	×	11·900	=	60·928
C_4H_8	5·97	×	11·400	=	68·058
					616·194

The oxygen used is obtained from the air, and is hence mixed with inert nitrogen, air consisting in the one hundred vols., of twenty-one vols. O., and seventy-nine N; and to supply the necessary 123 litres of O, 585 litres of air containing 462 litres of nitrogen must be used.

Thus before combustion we have ;

100 litres of gas, and 585 litres of air.

After combustion :

	Litres.	Grammes.
Water...	143·06	115·36
CO_2	62·89	123·97
N	464·46	585·41
	670·41	

And 616·194 gramme degrees of heat.

It will be observed that referred to the same pressure and temperature, the 685 vols. of gas and air are reduced to 670 by the combustion; the condensation is practically negligible.

A certain amount of the heat is absorbed in maintaining the water in the gaseous state, this may be estimated at 68,220 gramme-degrees for the 115,036 grammes, leaving 548,000 gramme-degrees of heat.

Now the temperature to which the resultant gases are raised, depends upon their specific heats, which it was formerly supposed did not vary with the temperature; recently (1881) however, **Mallard and Chatelier** have published results of their experiments proving that there is considerable increase in the specific heats of gases at high temperatures, though the rate of increase diminishes with the temperature.

The exact formulæ they deduce referred to molecular volumes are the following:

MEAN SPECIFIC HEAT AT CONSTANT VOL. = C.

For CO_2—

$$C = 6{\cdot}3 + {\cdot}00564\,t - {\cdot}00000108\,t^2$$

For OH_2—

$$C = 5{\cdot}91 + {\cdot}00376\,t - {\cdot}000000155\,t^2$$

For H. N. O—

$$C = 5 + {\cdot}00062\,t$$

Whence the mean specific heats for unit weights are as follows:

	2000°	1400°	1300°	1200°
OH_2	·712	·61	·58	.57
CO_2	·301	·27	·27	·26
N	·222	·21	·21	·20
O	·195	·18	·18	·18

The temperature attained is calculated from—

$$t = \frac{\text{heat disengaged}}{\Sigma\ \text{weight of constituents} \times \text{specific heat.}}$$

$$\therefore t = \frac{548{\cdot}000}{115{\cdot}36 \times {\cdot}712 \times 123{\cdot}97 \times {\cdot}301 + 585{\cdot}41 \times {\cdot}222}$$

$$= 2197^\circ\ \text{cent.}$$

The pressure of a volume of gas, when the volume is kept constant, is proportional to the absolute temperature; thus the pressure in atmospheres is

$$\frac{P}{P_0} = \frac{2470}{273}\text{; or } P = 1 \times \frac{2470}{273} = 9{\cdot}05 \text{ atmospheres.}$$

Supposing that instead of exploding the gas with just so much air as contains the theoretical amount of O, needful for complete combustion, we used gas and air in the proportion of seven to ninety-three, we should find, on the same hypotheses of instantaneous inflammation, absence of cooling, and constant volume, that the temperature attained by the gaseous mixture after combustion, would be 1288° C., and the pressure 5·7 atmospheres.

We will now consider how far we have to modify these figures for practical use, owing to the non-realisation of the above hypotheses.

First as to the rate of inflammation.

CHAPTER V.

RELATIVE SPEED OF COMBUSTION IN GASEOUS EXPLOSIVE MIXTURES.

WE shall here quote *in extenso* the researches of Berthelot and Vielle as given in the "Comptes Rendus de l'Académie des Sciences," Vol. 98, on the relative speed of combustion in gaseous explosive mixtures, as affording the most valuable information of a truly practical and experimental character. In the course of their experiments, these authors have taken care to observe, each trial, the time necessary for the pressure developed during the explosions at constant volume to attain its maximum. This observation is registered in curves. The inequality of these times is most important; in fact, the maximum pressure observed in a given volume is always less than the pressure which would be developed if the system maintained all the heat due to the reaction; for there is always a loss, owing to contact of the envelope and to radiation. The difference is inversely proportional to the volume, that is, as the mass of gas bears a less ratio to the volume of the containing vessel. Further, the slower the combustion the more this cause of error tends to increase. The duration of the combustions is otherwise very unequal, and varies with the variable state which is produced at the commencement of the phenomena, between the state of detonation (velocity of the wave of explosion, 2,810^{m} per sec. for H, 1,089^{m} for CO) and the state of ordinary combustion (34^{m} for H, 1^{m} for CO, according to Bunsen). The comparative retardation increases with the duration of the combustion.

The experiments were made with three different vessels, one of 300^{cc}, another of 1,500^{cc}, and a third of four litres capacity. The bomb of four litres was cylindrical and axially bored with two holes, one having a tube attached 63^{mm} long and 5^{mm} in diameter, at end of which the spark which inflamed the mixtures was produced, the other carried the registering piston. This projected 32^{mm} in the interior. The length of the internal axis of the bomb was 217^{mm}, so that the distance of the point of inflammation from the base of the piston was $217+63-32=248^{mm}$, of which 185^{mm} were in the vessel itself. Such is the maximum distance which the flame has to traverse before reaching the piston, at least as long as the latter is not displaced.

The 1,500^{cc} vessel is spherical, and similarly pierced along a horizontal diameter. The length of the inflammation tube is 53^{mm}, the diameter of the vessel 142^{mm}, the projection of the piston 32^{mm}. The distance of the initial point of inflammation from the end of the piston equals $142+53-32=163^{mm}$, of which 110^{mm} are in the vessel itself.

The 300^{cc} vessel is cylindrical, one of its bases is plane, and supports the registering piston, jutting in 32^{mm}; the other end is hemispherical, convex exteriorly, the inflammation tube is affixed at the junction of the cylindrical and spherical parts, and is 60^{mm} long. The distance of the initial point of inflammation from the base of the piston is 128^{mm}, of which 68^{mm} are in the vessel, this line is oblique to the axis. In every case the maximum was attained when the piston had moved about 20^{mm}.

In the experiments with NO_2 and CN the authors had recourse to central ignition, the flame going out in the tube. In this case the distance from the initial point of ignition from the piston was reduced to about 21^{mm}.

Here are the times elapsed, expressed in thousandths of a second, between the moment of ignition and that of production of maximum pressure.

I. Effect of Size of Receiver.
(Times elapsed in Thousandths of Second.)

	Vessel.		
Mixture.	300^{cc}	1500^{cc}	4000^{cc}
$H_2 + O_2$	1·04	—	2·14
$H_2 + O_2 + H_2$	1·67	—	4·22
$H_2 + O_2 + N_2$	2·67	—	6·87
$C_2O_2 + O_2$	12·86	—	15·51
$C_4H_4 + O_{12}$	2·86	—	2·23
$C_4N_2 + O_8$	1·55	4·50	—
$C_4N_2 + O_4 + \frac{3}{2} N$	3·20	2·74	—
$C_4N_2 + O_4 + 2 N_2$	10·35	15·12	—

In general it is evident that the largest requires a time proportioned to its capacity and the length between the initial ignition point and base of the piston. However, there are some irregularities, due to the perturbations produced in the neighbourhood of the inflammation point.

II. Effect of the Composition of the Mixture.

(Simple mixtures with total combustion 300^{cc}.)

$H_2 + O_2$	1·04	$H_2 + N_2O_2$	2·06	$C_4H_2 + O_{10}$	1·94
$C_2O_2 + O_2$	12·86	$C_2O_2 + N_2O_2$	15·39	$C_4H_4 + O_{12}$	2·86
$C_4N_2 + O_8$	1·55	$C_4N_2 + 4\,N_2O_2$	4·53	$C_4H_6 + O_{14}$	·83
				$C_2H_4 + O_{16}$	1·24

Carbonic oxide is slower than hydrogen, in accordance with previous knowledge, the ratio of the times (12·3) being between the state of detonation, 2·6, and that of ordinary combustion, ·34.

For cyanogen and hydrocarbons containing much hydrogen the velocity differs little from that of hydrogen, conformably to the velocity ratios deduced from the explosion waves (CN 1·3 according to wave, instead of 1·5; fornicue, 1·23 according to the wave, instead of 1·2; methyle, 1·2 according to wave, instead of ·8, &c.). It is always, then, the velocity of translation of the molecules which controls the phenomena.

The employment of protoxide of nitrogen instead of O slackens the action.

The absolute velocity is difficult to estimate. If it is admitted, to give an idea of the relative velocity, that the flame reaches the piston at the moment of maximum, the velocity will be about 100^{m} per second for hydrogen; about 8^{m} for CO; and 70^{m} for cyanogen. It falls to half for hydrogen burned into protoxide of nitrogen, to a third for cyanogen burned with the same gas, &c.

III. Effect of a more or less Complete Combustion.

(300^{cc}.)

$C_4N_2 + O_8$ ...	1·55	$C_4N_2 + O_4$ ...	1·06
$C_4N_2 + O_8 + 2\,N_2$	15·40	$C_4N_2 + O_4 + 2\,N_2$	10·35

It does not appear that the total combustion of cyanogen takes place in two parts, forming at first the total amount of CO, which would afterwards burn, for the total combustion is much quicker than the sum of the two separate effects. However, the incomplete combustion is the most rapid, perhaps owing to the existence of partial dissociation which slackens the total combustion.

IV. Influence of an Excess of One of the Components.

(4000^{cc}.)

$H_2 + O_2$	2·14		
$H_2 + O_2 + \frac{1}{39}H_2$	2·27		
$H_2 + O_2 + \frac{1}{19}H_2$	2·53		
$H_2 + O_2 + \frac{1}{9}H_2$	2·41		
$H_2 + O_2 + \frac{1}{2}H_2$	2·82		
$H_2 + O_2 + H_2$	4·22	$H_2 + O_2 + O_4$	8·16
$H_2 + O_2 + 2\,H_2$	5·95		
$H_2 + O_2 + 3\,H_2$	9·67	$H_2 + O_2 + 3\,O_4$	16·04

The combustion is slower in proportion to the excess of gas which does not burn, the retarding influence of the total oxygen being about double that of an equal volume of hydrogen, which answers to the translation velocity of the molecules of the former gas.

V. Influence of the Products of Combustion.

(300^{cc}.)

$C_2O_2 + O_2$ … …	12·86	$C_4N_2 + O_4$ … …	1·06
$C_2O_2 + O_2 + \frac{1}{2} C_2O_4$	27.18	$C_4N_2 + O_4 + \frac{3}{4} C_2O_2$	3·64
$C_2O_2 + O_2 + C_2O_4$	35·8	$C_4N_2 + O_4 + 2\,C_2O_2$	6·44

Slackening more and more marked; threefold for an equal volume of carbonic acid in one case, and six times for an equal volume of carbonic oxide in another. We can see, too, in the state of ordinary combustion, the rate of propagation of combustion is diminished by the mixture of gases already burned.

VI. Effect of an Excess of an Inert Gas.

(4 litres.)

$H_2 + O_2$ … … …	2·14
$H_2 + O_2 + \frac{1}{4} N_2$ … …	2·86
$+ \frac{1}{4} N_2$ … …	3·55
$+ N_2$ … …	6·87
$+ 2\,N_2$ … …	11·98
$+ 3\,N_2$ … …	24·45
$+ 4\,N_2$ … …	36·35

(300^{cc}.)

$C_2O_2 + O_2$ …	12·86	$C_4N_2 + O_8$ …	1·55
$C_2O_2 + O_2 + \frac{1}{2} N_2$	17·78	$C_4N_2 + O_8 + N_2$	6·09
$C_2O_2 + O_2 + N_2$	26·49	$C_4N_2 + O_8 + 2\,N_2$	15·4

$C_4N_2 + O_4$ … … …	1·05
$C_4N_2 + O_4 + \frac{3}{4} N_2$ … …	3·20
$+ 2\,N_2$ … …	10·35
$+ 3\,N_2$ … …	23·63
$+ 4\,N_2$ … …	29·78

Nitrogen retards the combustion of hydrogen and that of carbonic oxide, the first in a greater ratio; this shows that the phenomenon is not simply due to a lowering of the temperature, which is nearly the same in the two cases, but also to the greater inequality between the translation velocities of the gaseous molecules.

The inert gas at the same time lowers the temperature of combustion, which diminishes the translation velocity of the molecules, and also reduces the number of effectual collisions between molecules susceptible of reciprocal actions. Thus a notable excess of nitrogen reduces the velocity more than one of the two components with thrice the volume; in the oxy-hydrogen mixture the times for H, O, and N are proportional to 10, 16, and 24. The presence of an excess of one of the products still more retards the velocity; thus carbonic acid has more effect than nitrogen in the combustion of carbonic oxide.

In all these effects also intervene the inequality of the specific heats of carbonic acid and the variation in dissociation, produced by the presence of the components or products.

VII. Isomeric Mixtures (300^{cc}.)

$H_2 + N_2 + O_2$ ...	2·67	$C_2O_2 + N_2 + O_2$...	26·5
$H_2 + N_2O_2$ ...	2·06	$C_2O_2 + N_2O_2$ ...	15·4
$C_4N_2 + O_8$ ...	1·55	$C_4H_6 + O_{14}$ ...	·83
$2\,C_2O_2 + N_2 + O_4$	1·78	$C_4H_4 + H_2 + O_{14}$...	1·37

Combustion is slower in the least condensed mixtures, which are also those which in the same time disengage least heat, a double cause which at the same time diminishes the velocity of translation and the probability of effectual collisions.

VIII. MIXTURE OF TWO COMBUSTIBLE GASES.

$H_2 + O_2$	1·04	$H_2 + C_2O_2 + O_4$ ...	3·88
$C_2O_2 + O_2$	1·29	$H_2 + 2\,C_2O_2 + O_6$...	4·14
$H_2 + \frac{1}{2}\,C_2O_2 + O_3$...	2·57	$C_4H_4 + O_{12}$... ...	2·86
$H_2 + \frac{2}{3}\,C_2O_2 + O\,3\frac{1}{3}$	1·39	$C_4H_4 + H_2 + O_{14}$...	1·37

The rate of combustion is the mean in no case; the two gases appear to tend to burn separately each with its own velocity. It results that the maximum observed pressure does not correspond with an uniform state of combination of the mixture; consequently it is produced with certain irregularities, and is inferior to what it should be. Thus carbonic oxide and hydrogen, burned separately in oxygen, give the same pressure nearly, 10·1 atmospheres for one and 9·9 atmospheres for the other; for all mixtures one should get the mean; while experiment has led to lower totals, say 8·7 at equal volumes. There are the same reasons for the case of ethylene mixed with hydrogen compared to ethylene; the velocity of the combustion seems to point out that the hydrogen burns first.

IX. HYDRO-CARBONS. (Combustible elements combined).

(300^{cc}.)

$C_4H_2 + O_{10}$... ...	1·94	$C_2H_4 + O_8$	1·24
$C_4H_4 + O_{12}$... ...	2·86	$C_4H_6O_2 + O_{12}$ ...	1·42
$C_4H_6 + O_{14}$... ...	·83	$C_8H_{10}O_2 + O_{24}$ ...	2·89

The velocity of combustion of the highly hydrogenated gases is very near that of hydrogen, which seems to indicate that the hydrogen burns before the carbon, even in total combustion. These effects intervene in the momentary equilibria resultant from incomplete combination, such as the division of the O between two mingled combustibles, carbonic oxide and hydrogen for example, or even between the carbon and the associated hydrogen in the compound itself, as well as between the division of hydrogen between two combustibles, such as C and O.

This division in the first moments depends on the relative velocity of the combinations, and it may be quite different from that of definite equilibrium which would be established in the same system maintained at constant temperature during a suitable time.

A system suddenly cooled, such as that obtained after detonation, does not furnish a real measure of the affinities, because it may present a quite other distribution of the elements. A circumstance to which frequently too little regard has been paid.

The same eminent authorities have also taught us the following extremely valuable facts as to influence of density of the gaseous explosive mixture on the pressure developed.

Influence of the Density of Gaseous Explosive Mixtures on pressure.

It results, then, that up to nearly the highest known temperatures (3000–4000° air thermometer):

1. The same quantity of heat being furnished to a gaseous system, the pressure of the system varies proportionally to the density of the system.

2. The specific heat of the gases is sensibly independent of the density, as well at high temperature as near 0°.

All this is true for densities near that which the gases possess at 0° under normal pressure, which have varied in experiments from 1 to 2.

3. The pressure increases with the amount of heat furnished to the same system.

4. The apparent specific heat increases equally with this quantity of heat.

These conclusions, we repeat, are independent of all hypotheses on the laws of gases and of their physical or chemical constitution. They are the immediate translation of experiment.

CHAPTER VI.

WITZ' THEORETICAL CYCLES OF GAS ENGINES.

THE cycle really gone through by gas engines is substantially that we have defined in the first part of this work, but it undergoes deformations, of which we must now take account, since from them there results a diminution of its efficiency; these deformations constitute, in fact, imperfections in the real cycles. In this consideration we shall follow the theory laid down by M. Witz, and we shall do so as closely as possible, for the authority's sake.

The following hypotheses are made:—

1st. The detonation is instantaneous and the heating of the products of combustion is effected at constant volume.

2nd. The expansion takes place according to an adiabatic, with neither loss nor gain of heat: it is complete.

3rd. There is no back pressure on the piston during the in-stroke, the diagram is then closed by a line parallel to the axis of volumes, under a constant pressure equal to that of the atmosphere.

4th. The combustion of the products is complete.

Further, these conditions are not practically entirely realised, as may be seen by superposing the theoretical and real cycles.

The Lenoir engine is taken as the type of the engines without compression; the Otto and Simon engines correspond to the two sorts of motors with compression; lastly the atmospheric engines are represented by the Langen and Otto engine.

The deformations of the real diagrams are recognisable at a glance. Instead of a line parallel to the axis of pressure, we see a curve, more or less inclined, witnessing a gradual explosion; the heating thus does not take place at constant volume, and the temperature as well as the pressure on explosion is on this account greatly reduced. In a Hugon engine the maximum pressure developed in the cylinder is but 3·78 atmospheres according to M. Tresca; in the Lenoir engine this pressure does not reach 5 atmospheres, the deficiency is consequently at the least 30 per cent. In taking account, in the Otto engines, of the dilution of the mixed gases and of the volume of the injurious space (taken up by inert gases), we prove a nearly equal difference between the observed and calculated pressures; thus, a motor of four horse-power, fed with a mixture of one volume of gas to 7·57 volumes of air, has given, in full charges, diagrams whose maximum pressure is only 9·6 atmospheres, instead of 12 atmospheres.

The non-instantaneousness of the explosion is otherwise clearly shown by the study of the successive temperatures of the combustion products. From the knowledge of the volumes and pressures of these gases, we can easily deduce their temperature at no matter what point of the path. Besides, the maximum temperature is only reached after the point where the pressure has been a maximum. The explosive combustion is then far from being instantaneous, as supposed.

Furthermore, this fact was established some time ago and, as we have seen (p. 149), M. Vieille has been able to estimate the interval of that time which elapses between the commencement of inflammation and the production of maximum pressure: this interval is ·0267 secs. for a mixture of CO and O, and ·0016 for oxygen and hydrogen. It is much greater, as we shall see later on, for gaseous mixtures in practical use.

For the present, it is sufficient to state the fact and to call attention to its twofold consequences; on the one hand we see that the area of the diagram is lessened on this account; on the other the diminution of T, which results, lowers the value of the economical coefficients. In addition, T is less as the rate of combustion is slower; for the work transmitted to the piston absorbs so much the more heat, which evidently comes in as a reduction of the sum total of the heat produced by the combustion.

In the second place is supposed an adiabatic expansion, again a gratuitous hypothesis. The real diagrams allow us to estimate the influence of this deformation on the efficiency. In Fig. 55, the dotted line corresponds to the expansion without loss of heat; the full line of the diagram, taken from a Lenoir engine is markedly below it, and the loss of work strikes the eye.

The same observation can be made on the diagrams of the engines of Clerk, Simon, Langen and Otto, &c. On the diagram of the Otto Engine, we see it true as an inverse phenomenon. Instead of seeing the adiabatic curve above the real line, we find that the diagram remains above the adiabatic, as if the expansion took place not with loss of heat, but with gain. What is the cause of this effect, so paradoxical in appearance? Whence comes the heat which compensates both for losses and for the amount expended in work?

This question, to which most various answers have been given, has raised great debate in the scientific world, and the Institute of Civil Engineers, in London, has devoted several evenings to its discussion. In fact, if all agree upon the secondary cause of the phenomenon, opinions vary on the primary cause. The secondary cause is retarded combustion, explosion with after combustion (mit Nachbrennen); but why is the combustion retarded? By dissociation, say some; an effect of dilution, say, more simply, others. We shall soon see what irrefragable arguments are in favour of a third solution: for the present let us recognise that the peculiar phenomenon presented by the Otto diagram should still be considered as a deformation of the theoretical cycle, seeing that this slowness of combustion entails a considerable lowering of T. The incontestable advantages which result from it will be estimated in the sequel; the imperfection of the cycle cannot however be denied.

The loss of power which accompanies an incomplete expansion needs neither explanation nor proof.

The absence of back pressure arises from the way itself in which the cycle is closed; we supposed that the gases were restored to their initial state, by a cooling under constant pressure, before being discharged into the air. Thus in Fig. 56, the combustion products were cooled from *t'* to *t* along the path D B and thrust out of the cylinder along B A; similarly for the other types. But as a matter of fact the cooling is never complete, and the gases escape from the cylinder at temperatures far exceeding the initial temperature of the explosive mixture. M. Tresca indicates temperatures from 280 and 186° C., for the Lenoir and Hugon motors; M. Schöttler affirms that he has proved in the Otto engine more than 400° C. Instead of being carried to a refrigerator, the heat is dispersed in the atmosphere; it might be thought that this comes to the same thing, but this would be to strangely mistake, for it is precisely from this deformation of the cycle that back pressure results; its mean value is ·12 atmosphere in a well regulated Otto.

There still remains a last imperfection of the cycle, for the study of which the diagrams are of no use, that of incomplete combustion. It was pointed out for the first time by Mr. Bousfield, 4 April, 1882, at the Institution of Civil Engineers, London. This engineer declared that the gases discharged from an

Otto engine remained at times explosible and that they could give rise to a weak explosion on passing a burner.

The following are the results which M. Witz has obtained in exploding in a mercury eudiometer different mixtures of air and illuminating gas :—

Mixture.	Incomplete combustion per cent.
1 gas + 5·30 air	0·0
„ 7·35 „	2.6
„ 9·40 „	7·0
„ 11·60 „	12·0

These experiments made with the gas of the "Compagnie Continentale" do not confirm absolutely the observation of Mr. Bousfield; but they prove that account must be taken of the incomplete combustion of the combustible gas in engines.

To sum up, the real cycles are imperfect and the attained efficiency must necessarily be less than the theoretical efficiency.

Hence it comes about that gas engines, which are theoretically at the head of thermal engines, have to abdicate their high status which had been assigned them, and lose their superiority.

The study of this deficiency presents from all points of view the most lively interest. Besides, the sole means of explaining what really takes place in the cylinder of a gas engine is to reproduce by laboratory experiments the most important phenomena, and above all those most discussed, and to study them in all particulars. This is what M. Witz has done.

Consideration of an Explosion followed by Expansion.

The point was to reproduce artificially, so to say, the phenomena which occur behind the motor piston, while varying them at the will of the experimenter.

For this purpose a cylinder of cast iron was used by M. Witz, which is arranged vertically and has an internal diameter of $200{\cdot}1^{mm}$, and is 400^{mm} high. A piston with bronze packing moves in this cylinder from below upwards, under the action of the explosive mixtures. Its path is 323^{mm}; while it is 77^{mm} thick; and its weight is 14·5 kilograms. The resistance to motion produced by the friction of the bronze rings is equivalent to a force of 17 kilograms about. The force required therefore to lift the piston is 31·5 kilograms. The upward movement of the piston can be accelerated or retarded at will, by means of a counter weight and a brake. In the first case a cord attached to the end of the piston rod, and wrapped round a pulley, transmits to the piston the force of a mass of 75 kilograms falling down a groove; in the second case a pressure ring acts as a brake on the rod, and even allows all motion to be checked, if it becomes necessary to do so.

By this twofold arrangement, the velocity of the piston and consequently the rate of expansion, is under the control of the experimenter, and he can increase it from $\cdot 25^{m}$ to 10^{m} per second.

The explosive mixture is introduced under the piston through a stop cock, of simple action; reference notches on the rod of the piston indicate the volume of gas enclosed in the cylinder, and allow of its estimation with sufficient accuracy. The mixture is ignited by a spark from a strong induction coil, flashing at the bottom of a small cavity prepared in the cylinder wall.

The explosion occurs and projects the piston upwards; air holes, disposed in the cover, give exit to the compressed air; by closing them, a dashpot is made, which may be utilised to deaden the shock of the piston, and to weaken the concussion which always accompanies it.

The piston comes to rest when the resisting pressure of the air, its own weight and friction have absorbed its vis viva; it redescends slowly in proportion to the cooling and condensation of the combustion products.

The pressures developed under the piston are measured by a Richard's indicator, mounted on the cylinder and regulated by a cord attached to the piston rod, the diagrams thus drawn have their ordinates proportional to the pressures and their abscissæ proportional to the volumes occupied by the gas. A horizontal tuning fork inscribes its vibrations on a line parallel to the abscissæ, and marks the times with extreme accuracy; the fork employed made one hundred and twenty-eight simple vibrations per second, so that it was easy to observe less than $\frac{1}{200}$th of a second.

By examining the indicator-diagrams and estimating their area, it became possible to become acquainted with all the characteristic circumstances of an explosion and to calculate the work done, for a known volume of gas used, under given conditions. The explosive mixture, made in a water trough, was of a definite composition. By means of a caoutchouc bladder a variable volume was introduced into the cylinder, raising the piston to the prearranged mark. The spark flashed, the indicator traced its curve while the tuning fork marked a sinusoid more or less extended; one read at the same time on the same paper, the volumes and pressures of the gasses, the velocity of the piston's rise, the whole duration of the expansion, &c. A water or steam casing round the cylinder kept the walls of the enclosure at any desired temperature, whose thermal effect on the enclosed gases was perfectly known from preceding studies. All the conditions of the experiment were thus well determined.

The various springs of the indicator employed in these trials moved 1^{mm} for pressures of thirty-five grammes, seventy grammes, and one hundred and thirty-nine grammes, per square centimetre. The path of the registering cylinder was reduced in the ratio of 1 to 2·543.

These data are important for the calculation of the indicated work $\mathfrak{T}$. S being the surface of the piston of the experimental cylinder, in square centimetres, σ the area of the diagram in square mm., ϕ the pressure in kilogrammes per square centimetre, which causes the spring to yield one mm., and lastly r being the real path of the piston for each millimetre of the abscissa of the diagram (this path being expressed in metres) we shall have in kilogrammetres

$$\mathfrak{T} = S \phi \sigma r.$$

On making the calculations

$$\mathfrak{T} = \sigma \times {\cdot}112 = 6{\cdot}056 = \sigma \times {\cdot}028.$$

for the three springs used.

The area σ of the diagrams can be calculated by Simpson's formula, or better by Amsler's planimeter. Such is the method to which M. Witz had recourse to study the explosion phenomena which occur in the cylinders of gas engines.

Masterly researches have been already made with the greatest success on the combustion of explosive mixtures. Bunsen, Berthelot, Mallard, Le Chatelier and Vieille appear to have completely elucidated this important subject. However, none of these skilful and untiring physicists have operated under conditions such as are met with in practice, that is to say, in an enclosure closed with a moveable piston of large surface; their experiments have been conducted in closed vessels without expansion. In Witz' cylinder the expansion plays a very considerable part, and the observed phenomena present themselves in a new light.

The employment of great expansions presents in particular the double and precious advantage of limiting the temperatures and reducing the pressures developed in the explosion.

In limiting the temperatures, dissociation effects are averted, which certainly do not occur below 1500° C. By reducing and graduating the pressures, the oscillating motions are avoided, which have generally been only successfully suppressed by narrowing the passages, which is prejudicial to the rapidity and exactitude of the indication. The degree of expansion being known, it is easy to pass from the temperatures and pressures observed to the temperatures and pressures which would be developed in a vessel of constant volume, by the aid of the formulæ

$$\frac{P\,V}{T} = \text{const.} \qquad P\,V^{\gamma} = \text{const.}$$

The sole cooling action of the walls is then exerted on the gas.

We can thus give an account of all the circumstances which would be presented in a closed vessel by an explosion, with great accuracy and independently of dissociation effects.

The action of the wall could be studied by this process, indirectly it is true, but with interest, because the result was unexpected, in this way. It is possible to calculate, thanks to the latest works of MM. Mallard and Le Chatelier, the temperature produced by the combustion of a well-defined explosive mixture, such as the mixture of carbonic oxide and air, independently of all effect of dissociation and supposing the combustion complete.

We may thus consider that T is known, under the reserve just stated. But in expansion, the successive knowledge of the pressures and volumes leads to an approximate knowledge of the maximum temperature T′, which would be realised at constant volume, the sole action of the wall intervening.

T-T′ is, therefore, the loss of temperature due to the wall alone. The time during which the action is exercised is one of the data of the experiment. Dividing this time into *n* equal parts, during which the mean excess of the temperature of the gas over that of the enclosure is ε, and taking account of the successive values of $\frac{S}{V}$, it is permissible to apply the formula of cooling which is given for this cylinder; it is $V = \cdot058924\ \varepsilon^{1\cdot216}$, for an excess ε not exceeding 40° in a cylinder 200mm. in diameter and 400mm. high, for which the ratio $\frac{S}{V}$ of the surface to the volume is equal to 25.

For another cylinder it became

$$O = \frac{S}{V} \cdot02357\ \varepsilon^{1\cdot216}.$$

But for an excess ε, between 0° and 5°, the exponent would be equal to 1·203.

Mallard and Le Chatelier have observed that beyond 600° up to 2,400° of excess, the exponent may be taken equal to 2 in a cylinder with wet walls. It was of the greatest interest to ascertain according to what law the exponent varied in a cylinder of cast iron, similar to that of an engine. Several trials sufficed to arrive at this result. We shall give, in the following paragraph, the exact formula led to.

This indirect method may only furnish approximate results, but these results will have some value until some more direct and surer method has been devised.

Results of the Experiments.

Taking into account the volume and the surface of the tube of the stop-cock, between the cylinder and the plug-hole, the volumes and surfaces corresponding to the first four reference notches were as follows:

	Vol.	Surface.	$\frac{S}{V}$
1st notch	1066	906	·85
2nd "	2081	1109	·53
3rd "	3096	1312	·42
4th "	4111	1514	·35

A first series of trials showed that the phenomena depend in no way on the igniting spark; in fact, whether one or six Bunsen cells were used, or whether the induction coil was large or small, even whether to it were added a cascade of three bottles, the results of the detonation remained identical.

From the commencement of these researches, it was recognised that illuminating gas would present th most serious difficulties in experimenting, on accou of the great alterations in composition which it undergoes from one day to another in the same town. Certain experiments, made in the month of February, cannot be connected with those of the month of June, although they were made under identical conditions. Such a mixture as in winter shows incomplete combustion for an admission up to the third notch, burns completely in the spring.

These variations in the calorific power of illuminating gas necessitated special researches on an explosive mixture of constant composition. Recourse was had to a mixture of carbonic oxide and air. The carbonic oxide was made by the reaction of sulphuric acid on yellow prussiate of potash; a wash bottle retained the hydrocyanic acid which accompanies the gas in considerable proportions. The mixture was made over the water-trough; the gases were thus saturated with water vapour. It was considered possible to neglect this element in the calculation of the calorific power of the different mixtures used; the figures for the efficiency will thus be a little too small on this account.

The theoretical mixture of carbonic oxide and air is 2·404 vol. air to 1 vol. of combustible gas; by taking 2·675 vol. air to ensure complete combustion, we make a mixture which disengages, ·83 calories from each litre at zero.

At 15° the heat disengaged from each litre would be equal to ·78 cal.; at 64°, ·66 cal.

With pure oxygen, with $\frac{1}{20}$ air added, we should get

1·93 cal. per litre explosive mixture at 0°, and 1·82 cal. at 15°.

The proportion of the combustible being augmented, the heat varies, as one may see below:

	Per litre. Cal.
1 CO + 1·625 air	·78
1 CO + 2·150 „	·86
1 CO + 2·675 „	·83
1 CO + 3·200 „	·75

It is to be allowed that the gas of the "Compagnie Continentale" used, has a calorific power of 5,520 cal. per cubic metre of the combustible gas; this figure, based solely on the theoretical calculations before given, has appeared to fairly answer to the reality of the facts.

A simple verification is, in that, according to calculation, the contraction of the combustion products, after the condensation of the water vapour, ought to be equal to 15 per cent., for a mixture of 1 volume of gas with 9·40 air, and to 12 per cent. for a mixture of 1 volume of gas with 11·50 air; now, the water vapour being condensed, there were observed these same contractions in the mercury eudiometer.

From this coincidence would result a composition of hydrogen and hydrocarbons near the composition of the gas taken as a type. We must content ourselves with such a control, for it is impossible, at present, to be absolutely certain, and we must accept them as nearly accurate.

In other respects we have a sufficient foundation for the comparative experiments, the results of which we proceed to give.

The first object was to observe the result produced on an explosion by the velocity of the expansion. This velocity may be represented by $\frac{dl}{dt}$, the ratio of displacement of the piston to the time. The following tables plainly show the influence of the expansion velocity.

Mixture of 1 Vol. CO with 2·675 Vols. Air at 15° C.
Vol. of Mixture, 2·081 litres.

Time of Explosion. t	Path of Piston. l	Velocity. $\frac{dl}{dt}$	Theoretical Work. T	Work calc. from diag. T′	Useful effect per cent. η
Secs.	mm.	m.	kilgm.	kilgmt.	
0·17	254	1·5	688	22·0	3·2
·12	258	2·15	"	29·0	4·2
·11	"	2·35	"	34·0	4·9
·08	"	3·25	"	42·0	6·1
·05	"	5·20	"	53·0	7·7
·045	"	5·60	"	60·0	8·7

Mixture of 1 Vol. Illuminating Gas with 9·4 Vols. Air.
Vol. of Mixture, 2·081 litres.

t	l	$\frac{dl}{dt}$	T	T′	η
·48	122	·25	467	5·3	1·1
·47	127	·27	"	5·3	1·1
·40	"	·32	"	7·0	1·4
·39	132	·34	"	6·6	1·4
·31	140	·45	"	7·8	1·6
·23	147	·64	"	10·8	2·2

Mixture of 1 Vol. Illuminating Gas with 9·4 Vols. Air.
Vol. of Mixture, 3·096 litres.

t	l	$\frac{dl}{dt}$	T	T′	η
·53	188	·36	680	9·8	1·4
·42	203	·49	”	10·5	1·5
·40	”	·50	”	11·8	1·7
·35	211	·60	”	12·3	1·8
·25	229	·92	”	14·6	2·1
·16	”	1·42	”	17·4	2·6

Mixture of 1 Vol. Illuminating Gas with 6·33 Air.
Vol. used, 1·066 litres.

t	l	$\frac{dl}{dt}$	T	T′	η
·07	185	2·6	340	17·6	5·2

Mixture of 1 Vol. Illuminating Gas with 6·33 Air.
Vol. used, 2·081 litres.

t	l	$\frac{dl}{dt}$	T	T′	η
·15	259	1·7	663	17·6	2·6
·09	”	2·9	”	40·1	6·0
·06	”	4·3	”	50·5	7·5
·06	280	4·8	”	57·0	8·6

Commenced Feb. 24th, 1883, these experiments were continued till towards the end of July of the same year, and the trials placed in the same table have been taken from different days. The variations, sometimes considerable, of the gas furnished by the company should therefore introduce some discordance in the results, Nevertheless we can clearly see that the useful effect increases with the velocity of the expansion.

This result is still apparent with explosive mixtures of quite different richness, as the following table shows.

MIXTURES OF DIFFERENT PROPORTIONS OF CO. AND AIR.
Vol. used, 2·081 litres.

Composition. CO. Air.	t	l	$\frac{dt}{dl}$	T	T'	η
1+3·2	·17	221	1·3	646	19·4	3·0
	·13	236	1·6	„	26·5	4·1
1+2·675	·12	258	2·15	735	29·0	4·0
	·11	„	2·35	„	34·1	4·6
1+2·215	·08	„	3·1	760	41·7	5·5
	·07	„	3·7	„	50·2	6·6
1+1·625	·04	„	6·4	688	57·6	8·3

Several trials have been made with a mixture of one vol. of CO. with ·5 vol. air and ·075 vol. air in excess, but under these conditions, the charge so to say becomes shattering, and the results are less satisfactory by reason of the extreme velocity of the expansion, which exceeds 9·80 metres per second; the jerks of the indicator spring distort the curve and the estimation of the area of the diagram becomes very problematical.

The preceding tables nevertheless amply demonstrate that the useful effect increases with the velocity. This first point is obtained for us up to a velocity of six metres per second, which exceeds by much that of gas engine pistons.

The reader will see, Figs. 57 to 59 some curves traced by the indicator during the explosion of one vol. of gas with 6·33 air, each figure of the tables above given corresponds to one or more analogous diagrams.

Fig. 60 is a curious example of the effect of the velocity of the expansion. It is an experimental vagary.

This curve was got by closing the vent-holes in the cylinder cover. The compressed air above the piston then acted as a dashpot and retarded the expansion movement; thus the curve rises, and only falls from the cooling action of the walls, this piston being, so to say, immovable. This diagram, of such fantastic shape, will be useful to us in the study of slow-combustion.

The explosion diagrams do not only give the useful effect, but enable us to calculate the successive values of temperature and pressure, which would be observed in a closed vessel, without expansion, under the sole action of the wall. Let us apply it to some diagrams.

The diagram which has served as the foundation for these calculations is represented, Fig. 61. The mean velocity $\frac{dl}{dt}$ is equal to 2·02 metres per second. The initial temperature was 288° C. absolute measure, the detonation carries it suddenly to 474°, and the pressure rises from 1·033 kilogram to 1·7 kilogram, then the expansion commences. The absolute temperatures of the gas at each point of the curve are found from the formula $\frac{PV}{T}$ = constant. The pressures which the gas would have if the gas remained constant in vol. are given by the equation $P\,V$ constant, in which $\nu = 1{\cdot}3$. Lastly the absolute temperature attained in the same conditions are calculated from the formula $\frac{P}{P_1} = \frac{T}{T_1}$.

Here is an example of this calculation for the time ·016 seconds.

$$\frac{1{\cdot}7 \times 2{\cdot}081}{474} = \frac{1{\cdot}6 \times 3{\cdot}210}{x}$$

$$x = 687^\circ$$

$$1{\cdot}6 \times 3{\cdot}210^{1{\cdot}3} = x \times 2{\cdot}081^{1{\cdot}3}$$

$$x = 2{\cdot}81 \text{ kilog.}$$

$$\frac{2{\cdot}81}{1{\cdot}7} = \frac{x}{474}$$

$$x = 784^\circ.$$

This mixture has therefore taken ·112 seconds to attain a pressure of 7·88 kilograms, and an absolute temperature of 2,197° centigrade. At this moment combustion is completed, since the pressure and temperature fall immediately under the action of the wall. Fig. 61 exhibits to the eye all the phases of the phenomenon, the full curve is the real diagram, the dotted curve represents, on the other hand, the results of the calculation on a diminished scale, so as to avoid a too large figure. This cooling action of the wall is determined by the same fact, for we know how inferior the temperature attained is to the theoretical; instead 2,755, we find 2,197°. The total loss is thus 558°.

It is now the question to calculate elemental loss for each interval of time equal to ·016 second and to integrate the sum. Let us enquire what is, during each of these intervals, the mean excess of the gas temperature over that of the wall; then the mean values of $\frac{S}{V}$ being written opposite these excesses, let us apply the formula for the rate of cooling for the time ·016 second. We have no other unknown in this formula than the exponent of the excess, this is a function of the excess itself, which we should determine by trial. In the present case the equation $V = \frac{S}{V} \times \cdot 02357\ \varepsilon^{1\cdot 203 + \cdot 00048}$ corresponds with the facts. We have only to multiply V by ·016 to ascertain the loss in the interval.

Times ...	0	·016	·032	·048	·064	·080	·096	·112
Excess ...	186	399	653	873	940	1020	1062	1089

Mean excess	292	526	763	906	980	1041	1075
$\frac{S}{V}$ mean ...	4·7	3·8	3·2	2·95	2·86	2·75	2·7
Loss ...	4	12	37	79	106	143	167

The sum of the losses is then equal to 547° instead of 558°, this difference is negligible; the exponent would then equal $1\cdot 203 + \cdot 00048\varepsilon$, for a mixture of air, nitrogen and carbonic acid; and will only reach 2 at about an excess of 1660°. Millard and Le Chatelier were led to adopt the exponent 2 between the excess of 600° and 2,700°; we may remark that the mean of these two excesses is precisely 1,650°.

It is not necessary to apply this method to the products of combustion of illuminating gas, because the uncertainty there is on the theoretical value of T is too great.

Nevertheless, the result of this calculation, could not vary much from that jus made, seeing that the presence of water vapour modifies in no considerable degree, the cooling power of a gas, as M. Witz has shown in 1881; and who has proposed for gas engines the formula

$$\frac{d\varepsilon}{dt} = V = \frac{S}{V} \times \cdot 02357\,\varepsilon^{1\cdot 203 + \cdot 0005\varepsilon}$$

The following tables enable us to follow the progress of the combustion and all the phase of an explosion of a mixture of illuminating gas and air.

MIXTURE OF 1 VOL. GAS WITH 6·33 VOLS. AIR.

$$\frac{dl}{dt} = 4^{m}\cdot 30.$$

Time ...	0·	·023	·039	·044	·045	·046	·054
Expansion ...	1·	2·44	3·86	4·25	4·33	4·39	4·88
Press. observed...	2·1	1·6	1·22	1·12	1·10	1·05	·25
„ calculated...	2·1	5·1	7·05	7·35	7·39	7·18	1·96

The maximum pressure at constant volume was attained at the end of ·045 seconds; this calculation was made on the diagram in Fig. 57. The next refers to diagram of Fig. 58.

SAME MIXTURE.

$$\frac{dl}{dt} = 1\cdot 7$$

Time ...	0·	·023	·047	·063	·094	·109	·125	·141	·148
Expansion	1·	1·57	2·30	2·64	3·23	3·55	3·82	4·01	4·09
Press. obs.	1·45	1·40	1·28	1·25	1·18	1·15	1·12	1·10	·90
„ cal.	1·45	2·52	3·80	4·40	5·40	6·00	6·40	6·70	5·60

The maximum pressure would be produced at constant volume at the end of ·141 seconds.

Now let us consider a less rich mixture at different expansion rates:

1 VOL. GAS, 9·4 VOLS. AIR.

$\frac{dl}{dt}$ = ·25 metre.

Time ...	0·	·078	·156	·224	·312	·390	·468	·484
Expansion	1·	1·42	1·77	2·09	2·38	2.64	2·85	2·89
Press. obs.	1·165	1·165	1·165	1·165	1·165	1·165	1·160	1·100
,, cal.	1·165	1·83	2·44	3·03	3·60	4·10	4·53	4·02

SAME MIXTURE.

$\frac{dl}{dt} = \cdot 64^{m}$.

Time	0·	·078	·125	·164	·195	·219	·234
Expansion ...	1·	1·85	2·28	2·68	3·05	3·21	3·29
Press. observed...	1·25	1·25	1·25	1·25	1·20	1·15	1·11
,, calculated...	1·25	2·78	3·65	4.50	5·11	5·24	5·17

Collecting all these results:—

Composition.		Max. Press. kilog.	Duration of Combustion.	$\frac{dl}{dt}$
1 CO + 2·675 air	...	7·88	·112	2·02
1 gas + 6·33 air	...	7·39	·045	4·30
,, ,,	...	6·70	·141	1·70
1 gas + 9·4 air	...	5·24	·219	·64
,, ,,	...	4·53	·468	·25

There results, from these few figures, a most simple conclusion; the combustion is faster, and, consequently, the explosion pressure is greater as the velocity of the expansion increases.

This is a law of supreme importance in the question of gas engines. In fact, this influence of the expansion velocity is subordinated to an action of the wall; for, if not, how does the expansion velocity act on the explosion phenomena? This can only be by the cooling action of the metal surfaces which, being exerted during a more or less considerable time, abstracts the heat from the very source of the fire and diminishes the intensity of the re-action.

Now it is not only the rapidity of combustion which is subjected to this influence, but the area of the diagram is itself reduced, the work diminishes and the efficiency falls, as above proved. To make use of the greatest possible proportion of the heat of explosive mixtures, it is necessary to make the expansion of the products occupy as little time as possible and to reduce, as far as possible, the surface of the cylinder wall, that is to say, to make $\frac{S}{V}$ a minimum.

In this way we discover the phenomenon observed by Vieille, the maximum explosive pressure depends on the ratio of the cooling surface of the vessel to the volume of the gas. We recognise also immediately the advantage of realising the maximum of $\frac{Q}{V}$, the ratio of the quantity of disposable heat to the volume occupied by the explosive mixture; in other words, we discover that there is not only a theoretical advantage, but also a real practical gain in previously compressing the gases before detonation. Lastly, why the astonishing success of the Langen and Otto motor? Assuredly the cycle of the atmospheric engines is the most perfect, but this answer would not justify sufficiently the industrial superiority they at once attained, if we did not show that their cycle is less deformed than others, in consequence of the extreme rate of expansion of the gas. In fact in no other motor has a piston velocity equal to that in the atmospheric engines of Otto and Langen, Gilles and others, which have given the best results, been realised.

The action of the cylinder wall is thus the chief regulator of explosive phenomena.

It avails to quicken or retard combustion, to produce a slow and gradual combustion; there is no need to have recourse to theories of dissociation to explain this prolonged re-action of the combining gases. In fact, we reproduce this phenomenon under conditions such that dissociation is impossible, since the temperature in the cylinder never exceeds 1,400°. Dilution renders this effect more evident, it is plain ; because this volume of inert gas, in which the active explosion gas is wamped, acts no otherwise than the wall, that is to say, by cooling, but the prolonged combustion may be produced independently of dilution. This perfectly logical deduction of M. Witz' experiments appears important. It validates and confirms at each stage, the theory which Mr. Dugald Clerk so brilliantly sustained before his colleagues of the Institute of Civil Engineers, London. Along with this engineer, we consider that the combustion ought not to be designedly slackened nor retarded; this slackening is an inperfection which ought not to be striven for; Otto has therefore done wrong in doing so.

Unfortunately the retardation (the German "Nachbrennen" expresses the idea best) cannot be completely avoided. Why not? Because, says Mr. Dugald Clerk, heat is only developed gradually in the explosion of a gaseous mixture in proportion to the combination of a dissociated fraction; because, says M. Witz, the action of the wall can only be reduced, it cannot be totally suppressed. M. Witz is in agreement with Mr. Dugald Clerk when he affirms that the success of Otto is due to compression alone, and not to the extreme dilution of the explosive mixture in the product of the combustion of a precedent explosion. Without previous compression, he says, a motor cannot produce force economically, and under limited dimensions, whatever may be the dilution of the mixture, the method of introducing air to the cylinder, whatever manner of stratifying the layers we may employ, without compression there is no success possible. The proportions of the explosive mixture are the same in our latest machines as in that of the Lenoir engine, the duration is no less, there is no difference but in compression. The combustion or rather the heat of the inflammation is indeed quicker in the modern engine, because the volume of mixture used at each stroke is greater, and yet the time taken to completely inflame the mixture is no more than in the old type. The question is, in fact, to reduce, as far as possible, the surfaces in contact with a given volume of gas in the cylinder; that is the object in view. This important influence of the walls has been experimentally proved by M. Witz. Two parallel series of experiments were executed with an identical explosive gas, taken from the same gas holder, at temperatures of 15°, 64°, and 93°.

The combustible gas was carbonic oxide and illuminating gas.

Figures 62 to 65 are the diagrams obtained with carbonic oxide, the mixture containing 2·675 vols. of air.

Diagrams 62 and 64 correspond to the work in the hot cylinder; while 63 and 65 were taken from the cold cylinder.

For the first two the vol. of mixture was 1·066, for the second two 2·081 litres.

The course of the two groups of tracings is altogether different; when hot, the initial pressure is established so to say instantly; while when cold, the inclination itself of the line A B, Figs. 63 and 65 and the curvature of the summit A witness a slow combustion. The curvature of the expansion line is in other respects characteristic when hot, it answers to the equation $pv^{\cdot 22} = \text{const.}$ When cold the exponent is ·8. The combustion, therefore, is longer when cold than when hot, and in the diagram, when cold the diminution of pressure due to the progress of the expansion is nearly compensated by the increase which results from the prolonged combustion when hot; we see besides that the initial pressure is greater than when cold.

The diagrams taken with a mixture of one volume of gas with 9·4 of air are still more characteristic.

Here is the record of the numbers:—

	Vol. of Mixture.		Vol. of Mixture.
Fig. 66 hot	3·096	Fig. 68 hot	4·011
Fig. 67 cold		Fig. 69 cold	

When hot the expansion curves are represented by the formula $pv^{\cdot 16} = \text{const}$. At this temperature the diagrams show nothing peculiar, except Fig. 68 that the piston arrived at the end of its stroke before combustion was completed; the piston ceasing to move, the pressure immediately rises.

But at low temperature this effect is more clearly marked. We see, Fig. 67, that the expansion line is parallel to the axis of volumes; we even see it, Fig. 69, rise as the piston advances, a manifest proof that the combustion is only gradually accomplished with a slowness which is increased by the coolness of the envelope.

The influence of the cylinder wall on the mode of combustion is hence incontrovertible; the useful affect, moreover, increases or diminishes with the same action, as the following figures prove:—

EXPLOSIVE MIXTURE OF CO AND AIR.

		Efficiency.	Percentage benefit.			Efficiency.	Percentage benefit.
Cold	15	1·9	·7	Cold	15	3·0	·8
Warm	64	2·6		Warm	64	3·8	

We shall arrive at the same conclusion by the direct study of gas engines. Here, for example, are the values to be used as the index of γ in the equation $pv^\gamma =$ const. in the expansion curve of an Otto engine.

WORKING ON LOAD.

Temps. of the Envelope.	Values of γ.
45°	1·586
49·9	1·489
50·0	1·517

WORKING FREE.

45°	1·639
65°	1·557

We see that we have to lower γ as the temperature of the envelope with water in circulation rises.

The piston having kept the same velocity, it is evident that the combustion is retarded in contact with a cold wall. The useful effect also increases with the temperature of the wall. The motor studied consumed 1,152 litres per horse-power hour at 42°, and only 1,126 litres at 50°. M. Schöttler made the same observation at Hanover; his engine used 50 litres more when the temperature of the wall fell from 70° to 35°. In short, the influence of the wall on the combustion and on the efficiency is obvious and irrefutable. It is the cooling which chiefly deforms the cycle of gas engines and lowers their efficiency.

CHAPTER VII.

SOME FURTHER THEORETICAL DATA.

We include in this chapter some further theoretical data bearing more or less directly on the gas engine considered as an explosion engine, and we produce these remarks, as condensed from the works of the best authorities, in the form of notes, to the end of saving space.

Duration of Explosive Reactions.

Under this head we shall briefly consider :—

1. Origin of reactions.
2. Sensibility of the explosives.
3. Molecular velocity of the reactions, in homogeneous systems; conditions identical in all their parts.
4. Velocity of propagation of reactions.
5. Various ways in which an explosive can burn.
6. Combustion and detonation of explosives.
7. Experiments with $N_2 O_2$.
8. Thermo-chemical and Thermo-dynamic relations.

1. Reaction once set up may propagate itself either by—

    1. Simple progressive inflammation.
    2. Almost instantaneous detonation.

Preliminary work necessary to elevate the temperature of a portion of the explosive to a certain degree.

Every explosive reaction consists in a preliminary heating, which is transmitted layer to layer, successively elevating all the explosives to temperature of ecomposition. Shock, pressure, friction, mechanical actions are only efficacious in determining the preliminary heating, and occasionally in propagating the action in virtue of conversion of kinetic energy into heat. The decomposition of a given explosive may take place at very different temperatures and with velocities not less unequal. A substance slowly decomposable at a certain temperature can exist at much higher temperature, although for a time less and less long.

2. Sensibility to explosion :

Some substances are sensible to the least elevation of temperature, others to sudden pressure, and to a shock; another detonates with least friction: for instance, oxalate of silver explodes at 130°; sulphide of nitrogen about 207°; fulminate of mercury 190°; yet the fulminate is far more sensible to shock or friction than either the silver oxalate or nitrogen sulphide.

Sensibility of any substance increases with—

1. Initial temperature, because the heat disengaged by first portion of reaction is less dissipated by radiation, and rises to the

desired temperature degree a larger mass of non-decomposed matter.

2. With initial temperature high, the substance is in a state of *chemical tension*.

With shock or friction the comparative sensibility of two substances which decompose at same temperature, and with similar velocities, depend on the cohesion of substance, for cohesion determines the quantity of matter throughout which the shock or friction effect is distributed, and this of course influences the temperature to which substance is raised round the point affected primarily. Cohesion intervenes with direct inflammation, the same quantity of heat proceeding from combustion of previous portions can elevate to decomposition temperature a small quantity of explosive, while if it is distributed throughout a large volume, the desired effect may not be obtained. The quantity heated remaining the same, the substances being different, sensibility depends on the initial temperature of decomposition. Sensibility depends also on heat disengaged by decomposition, and on specific heat of the explosive.

3. (*a*) A distinction is to be made between the molecular velocity of the reactions, which is defined by the amount of matter transformed at a fixed temperature, under constant pressure, in unvarying conditions, and the propagation velocity of the reactions.

It would seem that when a substance is placed in the same conditions of temperature and pressure, and vibratory motion, &c., throughout its whole extent, that the reaction ought to be developed instantaneously through every part at once. The explosions of chloride of nitrogen and nitroglycerine appear to support this idea, but in reality molecular reactions require a definite time for action, even when disengaging heat. The duration of the reaction does not change the total quantity of heat disengaged by a given weight of matter; but if the products of combustion expand, the initial pressure will be less as the duration is greater.

(β.) A system, homogeneous, uniform conditions throughout, enclosed in athermanous vessel:

1. The molecular velocity of reactions increases with temperature (for ethers, according to an exponental function of T).
2. The T. increases up to a certain limit with the reaction.
3. The molecular velocity increases with the density of the matter, or the molecular velocity increases with the pressure in gaseous systems. Still the influence of the pressure is greater at the commencement than at the end of the action, seeing that the uncombined portion diminishes till a time arrives when the tension proper to this part, regarded independently of the rest, ceases to increase with the heating.
4. The molecular velocity depends on the relative proportions of its components.

At constant temperature, the combination is generally accelerated by excess of one of the components, and retarded by presence of an inert substance.

At variable temperatures; with regard to the reaction, a portion is retarded by excess of inert substances.

These are also generally slower, with excess of one of the components, than if equivalent proportions are used, the need of heating the excess matter counterbalancing the accelerative effect observed at constant temperature.

(γ.) The system may give up heat to surrounding objects although still homogeneous and similarly situated as regards temperature, &c., in all its parts.

The mass of matter employed which did not previously affect the results in principle, here plays a considerable part.

4. Velocity of propagation:

Homogeneous system subjected to different conditions in its different parts.

To propagate reaction, it is necessary to reproduce, in layer after layer, the same or more favourable physical conditions, which were called into being at one point.

Distinction insisted on between simple inflammation and true explosion. (See remarks on explosion wave.)

In 1876, Bunsen determined the combustion velocity of H_2 and O as 34 metres per second, and of CO and

O as only 1 metre per second at atmospheric pressure. Now, the explosion velocities of the same gases H and O may rise to as much as $3,000^m$ per second.

5. Multiplicity of ways of combustion.

Dynamite may decompose without flame, or may burn quickly or may explode either moderately or with extreme violence according to the process used in the first ignition. Abel's experiments in 1868 on guncotton also establish a similar diversity in the combustion. Gas mixtures are not liable to this kind of spontaneous combustion.

However strange at first sight this diversity may appear, thermo-dynamic principles are sufficient to completely explain it, by a suitable analysis of the phenomena of the shock.

In fact the variation of explosive action depends on the velocity with which the reaction is propagated and the more or less intense pressures resulting from it.

Taking the most simple case, that of an explosion consequent on a weight having fallen through a certain height. At first we felt obliged to attribute the observed results to the heat disengaged by the compression from the shock of a weight suddenly stopped. But calculation shows that the stoppage of a weight of several kilogrammes falling from $\cdot 25^m$ to $\cdot 50^m$ height could only raise but a fraction of a degree the mass of the explosive, if the resulting heat was distributed uniformly throughout it. It could not, therefore, attain thus a high temperature, such as 190° or 200° for example for nitroglycerine; the temperature to which it appears necessary to raise the whole mass, to entail explosion.

There must be another method by which the kinetic energy of the falling weight, transformed into heat, becomes the cause of the observed effects.

It is only necessary to admit that the pressures arising from the shock at the surface of the nitroglycerine are too sudden to be uniformly transmitted throughout the mass, and that consequently the conversion of kinetic energy into heat take place mostly in the layers reached by the shock. If this is violent enough, these layers will be thus suddenly raised to near 200°, and will immediately decompose, giving rise to a large amount of gas. The production of this gas is in its turn so sudden that the weight has no time to be displaced, and the sudden expansion of the products produces a new shock, more violent than the former, on the layers situated below. The kinetic energy of the new shock is converted into heat in the layers which it first reaches, and causes their explosion; and this alternation between a shock developing kinetic energy, which is converted into heat, and a production of heat, which raises the temperature of the heated layers to the degree of a new explosion, capable of reproducing a shock—this alternation transmits the reaction from layer to layer throughout the entire mass.

The propagation of the deflagration thus takes place in virtue of phenomena comparable to those giving rise a sound wave, that is to say, by producing an questionable explosion wave, which travels with a locity incomparably greater than that of simple flammation, caused by the contact of an ignited body, nd taking place under conditions where the gases xpand freely, in proportion as they are produced.

In fact, the reaction set up by a preliminary shock s propagated with a velocity which depends on the intensity of that shock.

It results that the explosion of a solid or liquid may be developed according to an infinite number of different laws, each of which is determined, *cæteris paribus*, by the original impulse.

The more violent the initial shock, the more sudden the combustion, and the greater the pressures during decomposition.

6. Burning and Explosion.

There is no absolute line of demarcation. Progressive combustion (properly so called) or progressive burning occurs where the cooling due to vessels or to inert matter lowers the temperature as far as is consistent with the continuation of reaction; all the heat produced is dissipated, except the fraction necessary to propagate the reaction in the next uncombined portions. This was the case in Bunsen's experiments.

Explosion Wave.

Berthelot and Vieille's experiments prove the existence of a new kind of undulatory motion of a mixed order, produced by the concordance of impulses both physical and chemical in the interior of the substance transformed. An explosion wave is produced, that is, a certain regular surface in which transformation occurs, and undergoes the same conditions of combination, temperature, pressure, &c.

This surface once produced travels from layer to layer in the entire mass, in consequence of the transmission of successive shocks of the gaseous molecules, brought into a state of most intense vibration from the heat disengaged in their combination, and transformed in situ or more rigorously with a slight relative displacement.

CHARACTER OF THE EXPLOSION WAVE.

1. Its velocity is uniform.
   Experiments with tubes closed or open at one or both ends give the same velocity.
2. Velocity depends on the nature of the explosive mixture, and not on the nature of the containing tube.
3. Velocity is independent of diameter of tube; above a certain point no sensible alteration between 5^{mm} and 15^{mm} diameter.
4. Velocity independent of the pressure, as is the case in the sound wave.
5. Thermal relation which exists between the velocity and the chemical constitution of the gas is more difficult to establish; it depends on temperatures,

whose valuation is uncertain, on account of dissociation and uncertainty of specific heats of gases at high temperatures.

However we can conceive the theoretical relation which determines the velocity of the explosion wave if we remark that the total energy of the gas at the moment of explosion depends on its initial temperature, and the total heat disengaged during combination.

These two data determine the absolute temperature of the system which is proportional to the vis viva ($\frac{1}{2} mv^2$) of translation of the gaseous molecules.

In other terms the excess of vis viva communicated to the molecules in the act of chemical combination is nothing else than the heat itself disengaged in the reaction; the pressure exerted by the molecules on the walls of vessels is the immediate representation of it, according to existing theories. We then arrive at a stage where the two classes of ideas, mechanical ideas and thermal ideas, tend to be no longer distinguishable.

Let us specify this conversion. The velocity of translation of the molecules at the moment of combination is proportional, in conformity with the relation of kinetic energy, to the square root of the ratio of the absolute temperature by the density of the gas referred to air, thus according to Clausius

$$\theta = 29{\cdot}354^{\text{met}} \sqrt{\frac{T}{\rho}}$$

In reality the physical notion of temperature does not enter into this calculation of the velocity, which only expresses that the vis viva of molecular translation of a gaseous system produced by reaction and containing all the developed heat is proportional to the vis viva of translation of the same gaseous system containing only the heat which it has at zero. Thus it seems that in the act of explosion a certain number of molecules among those which exist in the layer at first ignited are shot forward with the whole velocity corresponding to the maximum temperature, developed in the combination; their shock causes the reaction to occur in the next layer of gas and the motion is transmitted from layer to layer with a velocity, if not identical with, at least comparable to the velocity of the molecules themselves.

The transmission of the kinetic energy, in these conditions of extremely rapid action, may take place more readily between gaseous molecules of the same nature, in virtue of a sort of unison which co-ordinates similar motions, than between the molecules of a gas and the enclosing wall. The action is different in the case where the system in ignition has time to lose heat, communicated to other gases or to neighbouring bodies not susceptible of experiencing the same chemical transformation.

The velocity of explosion of H and O is the same in tubes of ·005 and ·035 metre diameter, viz. about 2,800 metres per second; with tube ·0015 metre the velocity is 2,341 metres.

ON THE DURATION PRECEDING THE ESTABLISHMENT OF THE EXPLOSION WAVE.

Distance of registering piston from point of inflammation. Metres.	Times observed.	Mean velocity.	
		From origin.	In each interval.
·02	·000275	72·72	72·7
·05	·000342	146·2	448·
·50	·000541	924·4	2261·
5·25	·002108	2491·0	3031·
20·190	·007620	2649·	2710·
40·43	·015100	2679·	2706·

The velocities rapidly increase up to the 5th centimetre, beyond which they are practically constant within limits of error.

The inflaming spark must be powerful, otherwise the preliminary variable state may be much longer.

With $H + O + 2N$ a velocity of 41·9 met. was got for 1st 2 centim.
„ „ „ 1068· „ next 5·25 met.
„ „ „ 1163· „ „ 10· met.

LIMITS OF DETONATION.

	H.	Air.	
Hydrogen	·233	·767	Velocity 1205 metres per sec.
	·217	·783	No propagation.
CO	$CO + O$		Velocity 1089 metres per sec.
	$2\,CO + N_2 + O$		No propagation.
	$2\,CO + N_2 + O_2$		Same.
	$CO + N_2 + O$		Negative results.
Marsh gas	$CH_4 + 4\,N_2 + O_4$		Velocity 1151 metres per sec.
	$CH_4 + 7·5\,N + O_4$		No propagation.

The limits would probably be lower, if experiments were made under pressure, and if stronger charge of fulminate were used to produce ignition.

Sometimes the flame after explosion wave ceases, runs back in the tube, especially in narrow tubes, which shows that limit of explosion is different from combustion limit.

Thus :—

	Detonation limit.	Combustion limit.
CO	Below 40 and even 60 per cent.	Below 20 per cent.
H and O	Below 22 per cent.	,, 6 ,,

Since the found velocities so nearly agree with θ from Clausius' equation, the molecules must retain nearly the total possible heat, and therefore dissociation can play but a small part in these experiments, probably on account of the high pressure and short time.

Also the velocity is independent of pressure, and therefore if dissociation occurs it must be independent of pressure.

Explanation of Tables.

1st Column. Composition of mixture before experiment.
2nd ,, ϕ Density of products after combustion air $= 1$.
3rd ,, N The molecular volumes of the elements, supposed gaseous, entering into the reaction.
4th ,, Q The heat envolved; water being supposed gaseous.
5th ,, $\sqrt{Q}$ The square root of Q.
6th ,, $\frac{Q}{N \times 6\cdot8}$, 6·8 being the constant of specific heats of elements at const. pressure; it is the temp. T of the reaction.
7th ,, θ Given from Clausius' equation for molecular velocity of translation $\theta = 29\cdot354\sqrt{\frac{T}{S}}$
8th ,, v Velocity found in experiment.

A SINGLE COMBUSTIBLE GAS WITH OXYGEN.

Mixture.	ϕ	N	Q	$\sqrt{Q}$	N×6·8=T	θ	v
H_2+O	·622	1·5	59000	243	5780°	2831^m	2810
$CO+O$	1·529	1·5	68200	261	6700°	1941	1089
$C_2H_2+O_5$	1·227	4·5	308100	555	10070°	2660	2482·5
$C_2H_4+O_6$	1·075	·6	321400	567	7880	2517	2209·5
$C_2H_6+O_7$	·985	7·5	359300	598	7050	2483	2363
CH_4+O_4	·924	4·5	193500	440	6320	2427	2287
$C V+O$	1·343	·4	262500	512	9650	2490	2195

TWO COMBUSTIBLE GASES ASSOCIATED WITH O.

Mixture.	ϕ	N	Q	$\sqrt{Q}$	N×6·8=T	θ	v
$CO+H_2+O_2$	1·075	3	127200	357	6230°	2236	2008
$2CO+3H_2+O_5$	·985	7·5	313400	560	6150	2321	2170
$C_2H_4+H_2+O_7$	·985	7·5	380400	617	7460	2551	2417
$C_2H_4+2H_2+O_8$	·924	9	439400	633	7180	2588	2579
$C_2H_6+H_2+O_8$	·924	9	418300	647	6830	2522	2250

COMBUSTIBLE GASES WITH O AND INERT GASES.

Mixture.	ϕ	N	Q	$\sqrt{Q}$	N×6·8 =T	θ	v
H_2+O	·622	1·5	59000	243	5780°	2831^m	2810
H_2+N_2+O	·796	2·5	59000	243	3470	1935	2121
·30 H ·7 air	·846	3·33	59000	243	2610	1820	1439
·267 H ·733 air	·868	3·8	59000	243	2287	1505	1201
·233 H ·768 air	·885	4·27	59000	243	2042	1409	1205
·217 H ·783 air	·895	4·56	59000	243	1903	1389	No propagation.
$CO+O$	1·529	1·5	68200	261	6700	1941	1089
$CO+N+O$	1·250	2·5	68200	261	4010	1661	1000 propagation doubtful.
·3 CO ·7 air	1·165	4·33	68200	261	2260	1236	No propagation.
CH_4+O_4	·923	4·6	193500	440	6320	2427	2287
$C_4H_4+2N_2+O_4$	·942	6·5	193500	440	4371	2002	1858
$CH_4+4N_2+O_4$	·951	8·5	193500	440	3347	1744	1151
$CH_4+7·52N+O_4$ CH_4+ air.	·958	12	193500	440	2371	1450	No propagation.

CHAPTER VIII.

CLERK'S THEORY OF THE GAS ENGINE.

We have previously referred to the theory of the gas engine advanced by Mr. Dugald Clerk, who divides gas engines into the three well-defined types of engines :—

1. An engine drawing into its cylinder gas and air at atmospheric pressure for a portion of its stroke, cutting off communication with the outer atmosphere, and immediately igniting the mixture, the piston being pushed forward by the pressure of the ignited gases during the remainder of its stroke. The in-stroke then discharges the products of combustion.
2. An engine in which a mixture of gas and air is drawn into a pump, and is discharged by the return stroke into a reservoir in a state of compression. From the reservoir the mixture enters into a cylinder, being ignited as it enters, without rise in pressure, but simply increased in volume, and following the piston as it moves forward, the return stroke discharges the products of combustion.
3. An engine in which a mixture of gas and air is compressed or introduced under compression into a cylinder, or space at the end of a cylinder, and then ignited while the volume

> remains constant and the pressure rises. Under this pressure the piston moves forward, and the return stroke discharges the exhaust.

Several minor types have been proposed, and many modifications of these three methods are used. A thorough understanding of these, however, renders it possible, says Mr. Clerk, to judge the merits of any other.

Types 1 and 3 are explosion-engines, the volume of the mixture remaining constant while the pressure increases. Type 2 is a gradual-combustion engine in which the pressure is constant but the volume increases.

Mr. Clerk, in the course of his experiments on gas engines, has found that 1,537° Centigrade is the temperature usually attained by the ignited gases in his engine, and he has accordingly investigated the behaviour of air under different conditions at this temperature.

Type 1. Suppose an engine to have a piston with an area of 144 square inches and a stroke of two feet. Let the piston move through the first half of its stroke drawing into the cylinder air; let enough heat be immediately added to this air to cause it to rise instantly to 1,537° Centigrade, and the piston continue moving forward under the pressure produced. If there be no loss of heat through the sides of the cold cylinder, but the temperature of the air fall only through performing work, how much work would be done when the piston completes its out-stroke?

The air before the heat is added is supposed to be at a temperature of 17° Centigrade (about 60° Fahrenheit) and the ordinary atmospheric pressure. In Fig. 70 the line marked adiabatic No. 2 is the curve showing the work which would be obtained under the supposed conditions. Fig. 71 is the indicator diagram such an engine would furnish. It is not necessary here to detail the calculations. The following are the results:—

1 cubic foot of air (at 17° Centigrade, and 760 millimetres mercury) remaining at constant volume requires to heat it to 1,537° Centigrade, an amount of heat equivalent to ...	26,762 foot-lbs.
Maximum pressure in lbs. per square inch above atmosphere	76·6 lbs.
Pressure at the end of stroke per square inch above atmosphere	19·6 lbs.
Mean pressure during available part of stroke	39·8 lbs.
Temperature of air at end of stroke... ...	1,089° C.
Work done on piston...	5·731 foot-lbs.

$$\text{Duty of engine } \frac{5{,}731}{26{,}762} = 0{\cdot}21.$$

As the engine is supposed to draw in air for half of its stroke, the last half of the stroke only is utilised for power; the mean available pressure calculated for the whole stroke is only $\frac{39{\cdot}8}{2} = 19{\cdot}9$ lbs. per square inch. There is a considerable pressure at the end of the stroke which could be made to give more work by expanding further; but for the purpose of comparison it is better to consider the three types of engines as each having a cylinder-capacity swept by the piston of two cubic feet, and in each case using in its operation one cubic foot of air at each stroke.

Type 2. Suppose an engine to draw into a pump one cubic foot of air, on its return stroke forcing the air into a reservoir at a pressure of 76·6 lbs. per square inch above the atmosphere. The motor-piston is now at the beginning of its out-stroke, and as it moves forward, air from the reservoir enters the cylinder, but as it enters it is heated to 1,537° Centigrade, without rise in pressure; the motor-piston sweeps through two cubic feet.

Fig. 72 shows the indicated card of this engine. *a b c d* is the pump diagram. Air at 17° Centigrade is taken in, compressed without loss of heat, the temperature rising under the compression to 217°·5 Centigrade. When it is equal to the pressure in the reservoir it is forced into the reservoir, as is shown on the line *b c*.

In all the operations no loss or gain of heat is assumed, except in doing work or in work being done on the air. In the motor-diagram from C to E the air is flowing from the reservoir following the piston, and the temperature is 1,537° Centigrade during the whole admission. At *e* the communication with the reservoir is cut off, and the temperature falls while the air is expanding doing work, until it reaches the end of the stroke, when the exhaust is discharged by the return-stroke of the piston.

For convenience the pump-diagram is shown on the motor one, and the shaded portion represents the work done by the air as the result of the cycle. As the heat is added while the air expands in volume, it takes considerably more to raise a cubic foot of air to the required temperature than in the case of type 1.

1 cubic foot of air (17° Centigrade and 760 millimetres mercury) at constant pressure requires to heat it from the temperature of compression 217·5° to 1,537° Centigrade heat equivalent to	32,723 foot-lbs.
Maximum pressure in lbs. per square inch above atmosphere	76·6 lbs.
Pressure at end of stroke above atmosphere...	19·6 lbs.
Mean pressure during available part of stroke	47·1 lbs.persq.in.
Temperature of air at the end of stroke ...	1,089° Centigr.
Work done on piston...	11,759 foot-lbs.

$$\text{Duty of engine } \frac{11{,}759}{32{,}723} = 0{\cdot}36.$$

Type 3. Suppose an engine to draw into a pump one cubic foot of air, on its return stroke, forcing it into a reservoir at a pressure of forty pounds above the atmosphere. The motor-piston is now at the beginning of its out-stroke, and as it moves forward air from the reservoir enters the cylinder while the piston sweeps through 0·39 cubic feet. At this point communication is cut off, and the temperature suddenly raised to 1,537° Centigrade. Hitherto the air has remained at the temperature of compression 150°·5. The pressure goes straight up to two hundred and twenty pounds above atmosphere. This is shown at Fig. 70, and also at Fig. 73, which is the diagram of this type of engine. *a b c d* is the compression diagram ; *a b e f* the motor diagram. The piston continues to move forward, and the air expands doing work. At the end of the stroke the pressure has fallen to 8·4 pounds per square inch above the atmosphere.

1 cubic foot of air (17° Centigrade, and 760 millimetres mercury) at constant volume requires to heat it from the temperature of compression 150·5° Centigrade to 1,537° Centigrade heat, equivalent to	24·416 foot-lbs.
Maximum pressure in lbs. per square inch above atmosphere	220 lbs.
Pressure at end of stroke	8·4 lbs.
Mean pressure during available part of stroke	47·8 lbs. per sq. in.
Temperature at middle of stroke	953° Centigrade.
,, end of stroke	648° ,,
Work done on the piston	11·090 foot-lbs.

$$\text{Duty of engine } \frac{11,090}{24,416} = 0{\cdot}45.$$

Fig. 74 shows the most important modification of this type ; in it, instead of a separate reservoir, a space is left at the end of the cylinder, into which the piston does not enter, and in this space the gases forming the inflammable mixture are compressed. The rise in pressure therefore commences at the beginning of the stroke instead of when the piston has travelled out. In this diagram the volume swept by the piston and the clearance space together are supposed to be equal to two cubic feet. Comparing the results obtained from these three modes under precisely similar conditions, the same weight of air heated to the same degree, and used in cylinders of identical capacity, there is a considerable difference in the results possible even under the purely theoretic conditions stated.

The relative work obtained from one cubic foot of air heated to the assumed temperature is shown below.

RESULTS FROM ENGINES OF EQUAL VOLUME SWEPT BY MOTOR-PISTON.

Type 1.	5,731	foot-lbs.	work obtained ...	0·21 duty.
„ 2.	11,759	„	„ ...	0·36 „
„ 3.	11,090	„	„ ...	0·45 „

That is, in an engine of type 1, if one hundred heat-units be used, twenty-one units will be converted into mechanical work. In type 2, with the same amount of heat, thirty-six units will be given as work, and in type 3 no less than forty-five units would be converted into work.

The great advantage of compression over no compression is clearly seen; by the simple operation of compressing before heating, the last type of engine gives for the same expenditure of heat 2·1 times as much work as the first. Compression, as used by the second type, does not afford so favourable a result; but even then the advantage is apparent, 1·6 times the effect being produced. By a greater degree of compression before heating even better results are possible. In an engine of type 3 expanding to the same volume after ignition as before compression, the possible duty D is determined by the atmospheric absolute temperature T′, and the absolute temperature after compression T; it is $D = \frac{T - T'}{T}$ whatever may be the maximum temperature after ignition. Increasing the temperature of ignition increases the power of the engine, but does not cause the conversion of a greater portion of heat into work. With any given maximum temperature the smaller the difference between that temperature and the temperature of compression, the greater is the proportion of added heat converted into work with any given amount of expansion. The greater the compression before ignition, the more closely the two temperatures come together, and the higher is the duty of the engine; neglecting in the meantime the practical conditions of loss. What compression does, is to enable a great fall of temperature to be obtained due to work done with but a small movement of the piston. In type 1 when the piston has reached the end of its stroke, the increase from the moment of ignition is only from one volume to two volumes; while in type 3, with the same total volume swept by the piston, it increases from one volume to five volumes. In the one case the ratio of expansion is two, while in the other it is five. This will be readily seen in Figs. 71 and 73. Now this increased expansion is not obtained at the cost of loss of average pressure; in type 1 the mean available pressure over the whole stroke is nearly

20 lbs. per square inch, while in type 3 it is 38·5 lbs. per square inch; that is, the compression-engine for equal size and piston speed has nearly twice the power of the other.

In the compression-engine with a maximum temperature of 1,537° Centigrade, the final temperature is 648° Centigrade, while in the other, with the same maximum temperature, the final temperature is 1,089° Centigrade. It is true that by expanding sufficiently the same final temperature can be obtained without compression, but the average pressure will be low, and consequently less available for the production of power. To produce anything like an expansion of five times without compression the pressure would fall below the atmosphere, and it would be necessary to expand into a partial vacum, and use a condenser and vacuum-pump, as is done in the steam engine. Compression makes it possible to obtain from heated air a great amount of work but with a small movement of piston, the smaller volume giving greater pressures, and thus rendering the power developed more mechanically available. The higher the maximum temperature the greater the amount of compression which can be used advantageously. There is a degree of compression for every temperature, beyond which any increase causes a diminution of the power of the engine for a given size.

The compression in Clerk's engine is 40 lbs. per square inch above the atmosphere, and he has accordingly confined himself to the comparison of engines employing this amount of compression with those using no compression. Now, seeing that this difference is produced between engines of types 1 and 3 by the simple difference of cycle, when there is no loss of heat through the sides of the cylinder, the question arises which engine would give the greatest effect, which engine in actual practice, with a cylinder kept cold by water, would come nearest to theory? In which of the engines would there be the smaller loss of heat?

The amount of heat lost by a gas in contact with its enclosing cold surfaces depends, first, on the difference in temperature between the gas and the cooling surfaces; secondly, on the extent of surface exposed; and, thirdly, on the time of exposure. It would be very difficult to make an accurate numerical comparison between the engines, but all to be shown is, that in the one the loss of heat must be less than in the other.

To compare the two engines, take equal movements of the pistons from a maximum temperature of 1,537° Centigrade. In the engine working without a compression this temperature is attained at the middle of its stroke, when the piston has moved through 1 cubic foot; the average temperature, while it moves to the end of its stroke, is about 1,300° Centigrade.

Now, in the compression-engine the maximum temperature is attained at a point when the piston has moved through 0·39 cubic foot: suppose it to move to 1·39 cubic foot, it has moved through 1 foot in the same time as the first engine. Then, as the temperature at the middle of the stroke is 953° (Fig. 73) it follows that the average during this movement is not higher than 1,000° Centigrade, but the space containing the heated air has increased from 0·39 cubic foot to 1·39 cubic foot, and with it the cooling surface; whereas the space containing heated air in the first engine has, during the same amount of movement, increased from 1 cubic foot to 2 cubic feet. It follows that as the temperature in the compression-engine is 1,000° Centigrade during the same time as the temperature in the first engine is 1,300° Centigrade, and as the surface in it for cooling is also less, the amount of heat lost by the air must be less in the portion of the stroke under consideration. During the portion of the stroke remaining, 0·61 cubic foot, the temperature of the heated air is low, falling to 648° Centigrade at the end of the stroke; it follows that very small comparative loss results. Altogether the loss of heat by the compression-engine will be the least.

It will be seen from Fig. 70 that there is a further cause of advantage. While the pressure and temperature are falling on adiabatic line 1, the work done by 1 cubic foot of air on expanding to the middle of the stroke at a temperature of 453° Centigrade is 7,888 foot-pounds, from 953° Centigrade to 648° is 3,202 foot-pounds, that is, 7,888 foot-pounds of work are performed by the engine during a movement of the piston equal to 0·61, while in the engine without compression a movement of 1·00 cubic foot only does 5,731 foot-pounds.

The compression-engine during this portion of its stroke has converted the heat entrusted to it into work at twice the rate of the other engine. This is a great point. Any method which converts the heat into work with the utmost possible rapidity, by reducing the time of contact between the hot gases and the cylinder, saves heat and enables the theory of the engine to be more nearly realised.

Taking all circumstances into consideration, it is certainly not over-estimating the relative advantage of the compression-engine to say that it will, under practical conditions, give, for a certain amount of heat, three times the work it is possible to get from the engine using no compression.

It will not be necessary to discuss the theory of type 2 in respect of loss of heat to the sides of the cylinder, as it is not much used, and has hitherto failed to yield results in any way equal to type 3. It will be seen, however, from Fig. 72, that the conditions are not so favourable for a minimum loss of heat as in type 3. The temperature from the moment of admission at *c*, to the point of cut-off at *e*, is kept constant at 1,537° Centigrade, so that the loss of heat must be great, both the surface exposed and the mean temperature being high. It is the less necessary to discuss this point in the slow-combustion engine, as the possibility of using a hot cylinder and piston reduces the loss by attaining a temperature not far removed from the entering air.

It will be interesting to calculate the amounts of gas required by these three types under the supposed conditions, and for this purpose an analysis of Manchester gas, and also of London gas, has been used as the basis of calculation.

ANALYSIS OF MANCHESTER COAL GAS, BY BUNSEN AND ROSCOE.

Hydrogen	45·58
Marsh-gas	34·90
Carbonic oxide	6·64
Olefiant gas or ethylene	4·08
Tetrylene	2·38
Sulphuretted hydrogen	0·29
Nitrogen	2·46
Carbonic acid	3·67
	100·00 vols.

Of this gas, 1 lb. at atmospheric pressure and 17° Centigrade measures 30 cubic feet, and evolves on complete combustion 10,900 heat-units Centigrade, equivalent to 15,146,640 foot-lbs. 1 cubic foot of this gas will therefore evolve on complete combustion heat equivalent to

$$\frac{15,146,640}{30} = 504,888 \text{ foot-lbs.}$$

To obtain an idea of the difference in heating-power [illegible] different gases, there is given here a recent [illegible]is of [illegible]don gas.

ANALYSIS OF LONDON COAL GAS.

	(A.)	(B.)
Hydrogen	50·05	51·24
Marsh-gas	32·87	35·28
Carbonic oxide	12·89	7·40
Olefines	3·87	3·56
Nitrogen	—	2·24
Carbonic acid	0·32	0·38

Taking the average of the two analyses, 1 lb. weight of this gas at atmospheric pressure and 17° Centigrade, measures 35·5 cubic feet, and evolves on complete combustion 12,500 heat-units Centigrade, equivalent to 17,370,000 foot-lbs., 1 cubic foot of this gas will therefore evolve, on complete combustion, heat equivalent to

$$\frac{17{,}370{,}000}{35 \cdot 5} = 489{,}268 \text{ foot-lbs.}$$

The difference between the heat evolved by these gases is but small. As Glasgow coal gas is of a high illuminating power, it will be richer in olefines, and the heat evolved per cubic foot will be somewhat greater. Taking 505,000 foot-lbs. as the amount of heat evolved by 1 cubic foot of coal gas, the result is probably very near the average to be obtained from the coal gas of most towns. The number of foot-lbs. required for one horse-power for one hour are 33,000 × 60 = 1,980,000. It therefore follows that if the whole heat to be obtained from gas were converted into mechanical work, 1 horse-power for one hour requires

$$\frac{1{,}980{,}000}{505{,}000} = 3 \cdot 92 \text{ cubic feet.}$$

Now, taking the three types of engines, the amount of gas required by each to give 1 IHP. per hour would be as follows :—

AMOUNT OF GAS REQUIRED BY THE THREE TYPES OF ENGINE.

Type 1. $\frac{3\cdot92}{0\cdot21}=18\cdot3$ cubic feet per HP. per hour.

Type 2. $\frac{3\cdot92}{0\cdot36}=10\cdot9$ „ „ „

Type 3. $\frac{3\cdot92}{0\cdot45}=8\cdot6$ „ „ „

If these engines be worked without loss of heat through the sides of the cylinders, but the expanding gases falling in temperature only through doing work, the above results would be obtained.

It is interesting to compare the consumption of gas by the engines in actual practice, to see in what order it stands. Results have not been obtained from engines of equal volume swept through by the piston, but it is at once seen that the order is in accordance with what is required by theory.

AMOUNT OF GAS CONSUMED BY THE THREE TYPES OF ENGINE HITHERTO IN PRACTICE.

1.	Lenoir	95	cubic feet per indicated HP. per hour.
	Hugon	85	„ „ „
2.	Brayton	50	„ „ „
3.	Otto	21	„ „ „

For the Lenoir and Hugon engines the results of experiments by M. Tresca, of Paris, have been taken, as stated, by Professor Thurston and the late Professor Rankine.

For the Brayton engine has been taken the result obtained by Professor Thurston, corrected for an error into which he has fallen. He states the consumption of the engine to be 32 cubic feet per IHP. per hour, and then goes on to say that on the brake 4 horse-power is obtained, while 8·6 is indicated. He has neglected to deduct from the gross indicated power in the cylinder, the pump-resistance, and thus calculates the consumption on the gross indicated, instead of on the available indicated power. The available indicated power is not more than 5·2 horse power, and the consumption is not less than 50 cubic feet per IHP. per hour.

For the Otto engine have been taken the figures given by Mr. F. W. Crossley. It is seen that the results are much what would be anticipated from the theory already developed. The difference between types 1 and 3 is greater than theory would indicate; but at the time the Lenoir engine was in use, the imperfection of the igniting arrangements and the rapid heating of the piston, and consequently of the entering gases, made its action diverge much more widely from theory than is the case with the Otto. The latter engine not only has the advantage of a better theoretical cycle but the arrangements are of a nature to secure a greater perfection of action, and consequently a still closer approach to theory. An amount of about 18 per cent of the heat used by it is converted into work, but, only 3·9 per cent. by the Hugon engine.

In types 1, 2 and 3, which have been discussed, it has been assumed that in each case the expansion doing work was carried to twice the volume of the air compressing.

Fig. 75 is a diagram from one of Clerk's engines which belongs to type 3. It will be observed that in this engine the expansion is only continued until the volume of the hot gases becomes equal to the volume before compression.

Taking the amount of work to be obtained from a cubic foot of air compressed to 40 lbs. above the atmosphere, and then heated to 1,537° Centigrade, expanding as the piston moves to its volume before compression, and then exhausting, it will be found to give the following results :—

1 cubic foot of air (17° Centigrade and 760 millimetres mercury) at constant volume requires to heat it from the temperature of compression 150·5° Centigrade to 1,537° Centigrade, heat equivalent to . . .	24,416 foot-lbs.
Maximum pressure in lbs. per square inch above atmosphere	220 lbs.
Pressure at end of stroke in lbs. per sq. inch .	49 lbs.
Mean pressure during available part of stroke above atmosphere	89·8
Temperature at the end of the stroke . .	953° Centigrade
Work done on the piston	7,888 foot-lbs.

$$\text{Duty } \frac{7{,}888}{24{,}416} = 0{\cdot}32.$$

Now, the work actually given by 1 cubic foot of combustible mixture in Clerk's engine, as will be seen from Fig. 75, is 6,851 foot-lbs. The full lines are the diagram-lines from the engine; the dotted lines are the lines of compression and expansion without loss or gain of heat, except by work done on or by the air under similar conditions of temperature and compression. It will be observed that the compression line and the dotted line are very close together; no heat seems to be lost to the sides of the cylinder during compression; the loss of heat to the water-jacket is balanced by the gain of heat from the piston, which must necessarily be much hotter than the cylinder-sides, as it only loses heat by contact with the cylinder and by the circulation of air in the trunk. The temperature attained at the commencement of the stroke is in both cases identical, 1,537° Centigrade; the temperature at the end of the stroke without loss of heat is 953°; the temperature in the cylinder at the end of the stroke is 656° Centigrade. This appears a very small loss of heat from a flame filling the cylinder, considering the surface exposed and the great difference of temperature between the ignited gases and the enclosing walls. Is it to be concluded, then, that the loss of heat to the cylinder during the time of the forward stroke is only 953°—656° = 297°Centigrade. On this assumption the duty of the engine would be—

$$\frac{6{,}851}{24{,}416} = 0{\cdot}286,$$

and the comsumption of gas per indicated HP. per hour would be—

$$\frac{3\cdot92}{0\cdot286} = 13\cdot7 \text{ cubic feet};$$

but the consumption is 22 cubic feet per indicated HP. per hour, so that there has in some way been lost much more heat than is to be accounted for by the temperatures as determined by the diagram. The duty of the engine is —

$$\frac{3\cdot92}{22} = 0\cdot178.$$

The duty of the engine expanding to the same volume as the mixed gases before compression is —

		Gas required per IHP. per hour. Cubic Feet.
Duty without loss of heat to sides of cylinder	0·323	12·1
Duty with loss of heat as shown by diagram .	0·286	13·7
Duty as determined by experiment . .	0·178	22·0

Now, the number of cubic feet of combustible mixture required to produce 1 HP. for one hour in Clerk's engine is —

$$\frac{1{,}980{,}000}{6{,}851} = 289.$$

The amount of gas in the engine per cubic foot of mixture, $\frac{22}{289} = 0\cdot0761$ cubic foot, or $\frac{1}{13}$ of the total volume of gaseous mixture passed into the engine. If only the amount of gas necessary to heat the air to the required temperature is present, 1 cubic foot requires 0·0482 cubic foot of coal gas, or about $\frac{1}{21}$ of its volume; that is, although to heat up a cubic foot of inflammable mixture from 150° Centigrade to 1,537° only 0·0482 cubic foot of coal gas is required, yet although there is present 0·0671 cubic foot, or 1·58 times the amount necessary, the temperature does not rise any higher. Why is this?

Before going into the question, it is better to determine as nearly as possible what becomes of 100 heat-units used by the engine. The exhaust being discharged at a temperature of 656°, and the temperature of the air before compression being assumed at 17°, it follows that the exhaust from 1 cubic foot carries away with it (656 — 17) × 17·61 = 11,253 foot-lbs.

The work done by the cubic foot of mixture is 6,851 foot-lbs., and the equivalent in foot-lbs. of the gas present in 1 cubic foot of explosive mixture is 0·0761 × 505,000 = 38,430 foot-lbs. The heat is therefore disposed of as follows :—

	Foot-lbs.	Heat-units per cent.
Work done by 1 cubic foot of mixture .	6,851	17·83
Mechanical equivalent of heat discharged with the exhaust	11,253	29·28
Mechanical equivalent of heat passing through sides of cylinder . . .	20,326	52·89
	38,43	100·00
		0

This investigation is only approximate. The determination, with anything like possible physical accuracy, would require an examination of many points involving months of continuous work. For the present, however, it is only necessary to discuss the principles in such a manner as to clearly show where original research is required. More than one half of the total heat given to the engine passes through the sides of the cylinder and is lost. How is this enormous loss of heat sustained, while only a comparatively small fall of temperature takes place below the adiabatic curve.

This leads back to the question of what becomes of the gas present in excess of the amount necessary to raise the temperature to 1,527° which has already been noticed. At this point it is necessary to consider the gas engine as something different from a hot-air engine.

The chemical phenomena attending combustion now require consideration. If two volumes of hydrogen be mixed with one volume of oxygen (the proportions necessary for complete combination of both gases to form water), and be ignited in a closed vessel in such a manner that the maximum pressure may be measured, it will be found that the pressure is a much lower one than would be expected if the complete combination of the two gases took place at once, and the whole heat due to this combination were developed. That this is not due to loss of heat to the sides of the vessel has been shown by Bunsen. He proved that the rate of rise in pressure is exceedingly rapid compared to the rate of fall of pressure. The time taken for the inflammation of the whole volume of mixture is the time of attainment of the maximum pressure. In his experiments, he used only a very small tube, which contained a volume of gaseous mixture, 8·15 centimetres long, by 1·7 centimetre in diameter, and the entire length of this column was traversed by the electric spark, in order that the inflammation of the whole mass in the tube might be as nearly instantaneous as possible. In practice he succeeded in producing a maximum temperature in so short a time as $\frac{1}{4{,}000}$ part of a second. By examining the light from the explosion through a revolving disk provided with radiating segments, the rate of revolution of the disk being known, he determined the duration of light within the tube, and therefore the duration of a temperature not far removed from the maximum.

The duration of the illumination was found to be $\frac{1}{38}$ of a second. A maximum pressure, obtained in so short a time, with a duration so relatively long, makes it impossible that loss of heat through the sides of his tube could have affected his experiments. The cause, therefore, of the pressure falling so far short of what it would be if the combination took place completely, is simply this, that the temperature is so high that complete combustion is impossible. The temperature, and, therefore, the pressure produced by the combination of any gases, is limited by the dissociation or decomposition of their products of combustion.

When any two gases combine, say (H) and (O) to produce water, what happens is this. The temperature rises till a point is reached, when any further rise would decompose the water which is already formed; and if the gases are kept at this temperature, no further combination will take place. If the temperature is lowered, further combination takes place whilst it is low enough to allow of the existence of steam without decomposition.

The temperature at which steam can exist as steam without its partial resolution into hydrogen and oxygen gases is not a high one. At 960° to 1,000° Centigrade Deville has proved that it commences to decompose, and at 1,200° Centigrade, considerable decomposition takes place, the amount of decomposition increasing as the temperature rises: for each temperature there is a proportion of steam to free gases which is constant, and does not change till the temperature changes. The same law holds true for carbon dioxide; at high temperature it decomposes into carbonic oxide and free oxygen.

Bunsen attempted to determine the temperature attained on the explosion of a mixture of hydrogen and oxygen, a pure electrolytic mixture. He found that the maximum pressure attained by such a mixture is 10 atmospheres, the temperature before ignition being

5° Centigrade. From this he calculated the temperature produced, but in doing so, as Berthelot afterwards pointed out, he neglected the fact that when these gases combine, 3 volumes of the gases form 2 volumes of steam-gas, and consequently if complete combination is assumed, and it be supposed that the pressure is produced by steam only, the volume before ignition must be calculated at two-thirds of that taken by the mixed gases. But as it is known that combination is incomplete at the lowest assignable temperature of the combustion, and it is not possible to tell the amount of combination at a given pressure without knowing the temperature, this cannot be assumed.

As in determining temperature by an air thermometer it is necessary that the amount of air in the thermometer should be constant at the different temperatures, it is evident that the temperature of an explosion cannot be known from the increase in pressure unless the chemical changes taking place do not alter the volume of gases under observation.

In calculating the temperatures attained in Clerk's engine, this fact has been kept in view by him. The capacity of the space at the end of the cylinder was carefully taken by filling with water and weighing the water. As the proportion of the combining gases to the excess of oxygen or free nitrogen is very small, only one-thirteenth of the whole volume used being combustible gas, the space may be considered as simply filled with heated air, and the contraction caused by the formation of H_2O and CO_2 neglected, especially as an increase in volume follows the combination of the olefines with oxygen. 2 volumes of H combine with 1 volume of O, forming 2 volumes of steam. 2 volumes of marsh-gas (CH_4) require for complete combustion 4 volumes of O, and form 4 volumes of H_2O and 2 volumes of CO_2. 2 volumes of carbonic oxide (CO) unite with one volnme of O, forming 2 volumes of CO_2. If the olefines in coal-gas be taken as of an average composition of C_3H_6, then 2 volumes require for complete combustion 9 volumes of oxygen, forming 6 volumes of H_2O and 6 volumes of CO_2.

Now, taking the composition of coal gas as below, the noted amounts of oxygen are required for combustion, and the given volumes of the products are formed—

H = 50 vols. requires 25 vols. O = 50 vols. H_2O produced.
CH_4 = 33 vols. requires 66 ,, O = 99 vols. CO_4 & H_2O ,,
CO = 13 vols. requires 6·5 ,, O = 13 vols. CO_2 ,,
C_3H_6 = 4 vols. requires 18 ,, O = 24 vols. CO_2 & H_2O ,,
100 + 115·5 = 225·5 gives 186 vols.

The amount of contraction due to complete combustion of this coal gas is small even when burning with pure oxygen, 225 volumes of the mixed gases becoming 186 volumes after combustion. When diluted with nitrogen the proportion of contraction is less and introduces no serious error. With a mixture of one volume of gas to 12 volumes of air, 125 volumes of the mixture before combination become 122 volumes when completely combined, at the original temperature, assuming the water to remain gaseous. If the curve of the dissociation of water and carbonic dioxide were known it would be possible to show on the indicator diagram the reserve of heat available at each point of the fall.

What the engineer requires of the scientific chemist is a curve of the dissociation of water and carbonic acid at temperatures ranging from the maximum produced by combustion down to the point at which it may be safely assumed that complete combination is possible.

In Fig. 57 the dotted line shows a fall of temperature, by hot air doing work without loss of heat through the cylinder, and the black line shows the actual fall of temperature in Clerk's engine, with loss of heat through the sides of the cylinder. It is evident then that the cause of so near an apparent approach to theory is, that at the maximum temperature, complete combination of gases with oxygen is impossible, and cannot take place until the temperature falls. As the temperature falls the gases further combine, until a temperature is reached at which combination is complete.

The loss of heat through the sides of the cylinder is, therefore, much greater than would appear from the diagram. In calculating the efficiency of the gas engine, all previous observers have assumed that the loss of heat to the cylinder is to be obtained from the comparison on the indicator-diagram of the actual expansion-line with an adiabatic line from the same maximum temperature and pressure. Professor Rücker, of Leeds, was the first to point out the necessity of taking into account the phenomena of dissociation in making such comparisons. Accordingly, all previous estimates of efficiency, based on the indicator diagram, are much too high.

The gas engine, then, differs from the hot air engine, using heated air, in this, that the temperature is sustained, notwithstanding the enormous flow of heat through the sides of the cylinder, by the continuous combination of the dissociated gases.

In The Lenoir Gas Engine, a paper read before the Franklin Institute, in 1866, by Mr. Slade, it is pointed out that "the temperature at the end of the stroke would be 2,156° Fahrenheit (1,180° Centigrade). The final temperature, supposing there be no leakage, is 1,438° Fahrenheit (781° Centigrade), and the difference, 718° Fahrenheit (399° Centigrade), is the quantity of heat absorbed by the water-jacket by which the cylinder is surrounded."

"It will be observed that the explosion takes place so late in the stroke that there is a considerable available pressure at the end of the stroke, which of course is not utilised."

Now, if the Lenoir engine had only lost this amount of heat through the sides of the cylinder it would have been very economical and would have approached theoretic consumption; but the causes of loss are so great that it never did come anything near this figure, and an error is introduced, according to Mr. Clerk, through neglecting the effects of dissociation.

Interesting information, however, is to be obtained from this paper as to the proportion of gas and air in the mixture used by the Lenoir engine. When these diagrams were taken the maximum temperature after ignition was 1,356° Centrigrade; now in Clerk's present engine the maximum temperature is 1,537°; it follows that Lenoir used a more diluted mixture as the temperature after ignition was lower. The engine could not have been using an ignitable mixture containing more gas than one-fourteenth of its volume—a mixture which Mr. Clerk finds to be easily ignited at ordinary atmospheric pressure. The statement is often made that such a mixture will not explode except it be first compressed; this is incorrect, it is possible to ignite even a weaker mixture without compression. Coquillon* has determined the limits between which a mixture of marsh-gas (CH_4) and air can be exploded. Mixtures of marsh-gas and air in different proportions were introduced into a eudiometer and fired by the electric spark, with the following results:—

Marsh-gas, 1 volume; air, 5 volumes: the spark is without effect. Marsh-gas, 1 volume; air, 6 volumes: explosion only occurs in a succession of shocks. This is the first limit of possible explosion; the marsh-gas is in excess. Marsh-gas 1 volume, and 7, 8 and 9 volumes of air gave a sharp explosion. With 12, 13, 14, 15 volumes of air for 1 volume of marsh-gas the explosion occurs, but grows gradually weaker. With 16 volumes of air the effect is reduced to a series of slight intermittent commotions. This is the second limit; the air is in excess.

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* Journal of the Chemical Society, vol. i., 1877, p. 166; and Comptes Rendus de l'Académie des Sciences, 1876, vol. xxxiii., p. 709.

In the Lenoir engine the time, from the beginning of rise in pressure to the attainment of maximum pressure, is found to be from one twenty-seventh to one-thirtieth of a second; when the ignitions are late it takes longer, one-twentieth of a second being required; that is, the flame has spread completely through the mass in one-twentieth part of a second.

Now, in Clerk's engine, calculating from the moment when the ignition port is opening to the flame, to the moment of maximum pressure as found from the diagrams, it has been ascertained that the time occupied is an average of one twenty-fifth of a second, a time nearly identical with that found for the Lenoir engine.

If it be admitted that the flame has spread completely through the mass when the maximum pressure is attained in the Lenoir engine, it cannot be supposed that it has not spread in like manner throughout the mass of ignitable mixture in the modern compression engine. Maximum pressure is the only outward indication of complete inflammation; by complete inflammation is not meant the thorough chemical combination of the active gases present, but the spread of the flame through the entire mass. That when maximum pressure has been reached complete inflammation has also been attained has hitherto been considered self-evident. The theory has been advanced by Mr. Otto that in the modern compression-engine attaining maximum pressure at the beginning of the stroke, the flame has not spread throughout the mass of the ignitable mixture in the cyclinder; but that as the piston moves forward the pressure is sustained by the gradual spread of the flame. This supposed phenomenon has been called slow combustion; if it has any existence it should be called slow inflammation. It has a real existence in the Otto engine, Mr. Clerk infers, only when it is working badly; but even then maximum temperature is attained, and very distinctly marks the point of completed inflammation.

The time taken to attain maximum pressure is longer in a large engine than in a small one, because the distance through which the flame has to travel is greater. During the investigation already referred to, Professor Bunsen determined the celerity of the propagation of ignition through a pure explosive mixture of hydrogen and oxygen in the following manner: the explosive mixture was allowed to burn from a fine orifice of known diameter, and the rate of the current of the gaseous mixture was carefully regulated by diminishing the pressure, to the point at which the flame passed back through the orifice and ignited the gases below it. This passing back of the flame occurs when the velocity with which the gaseous mixture issues from the orifice is inappreciably less than the velocity with which the inflammation of the upper layers of burning gas is propagated to the lower and unignited layers.

The rate of the propagation of the ignition in pure hydrogen was found to be 34 metres per second. In a maximum explosive mixture of carbonic oxide and oxygen it was not quite 1 metre per second.

Mallard* has determined the rapidity of the propagation of inflammation through mixtures of coal-gas and air by this method, and found that the maximum rate of propagation was attained with a mixture of 1 volume of coal-gas with 5 volumes of air, and it is 1·01 metre per second. One volume of coal-gas with $6\frac{1}{2}$ volumes of air gave a rate of 0·285 metres, or 11 inches per second.

This is the rate of ignition, it must be remembered, at constant pressure ; in a closed tube fired at one end it would ignite with much greater rapidity. In a closed space the conditions of inflammation are quite different. The ignited portion instantly expands, compressing the portion still remaining, and thus carries the flame further into the mass, so that to the rate of ignition at constant pressure is added the projection of the flame into the mass by its expansion. To determine from the rate of ignition at constant pressure the time necessary to completely inflame a given volume of mixture at constant volume is a very complicated problem, which it is probable can only be solved experimentally.

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* Journal of the Chemical Society, 1877, vol. i., 632 ; Thorpe on "The Theory of the Bunsen Lamp."

Mr. Clerk has found it possible to ignite a whole mass in any given time between the limits of one-tenth and one-hundredth part of a second, by so arranging the plan of ignition that a small volume of gaseous mixture is first ignited, expanding and projecting a flame through a passage into the mass of inflammable mixture, and thus adding to the rate of ignition the mechanical disturbance produced by the entering flame. He has succeeded by this means in producing maximum pressure in one-hundredth part of a second in a space containing 200 cubic inches. This rate of ignition is too rapid, and would not give the engine time to take up the slack in bearings, connecting-rods, &c. But by firing a mixture with varying amounts of mechanical disturbance almost any time of ignition can be obtained between $\frac{1}{100}$ and $\frac{1}{10}$ of a second. It does not matter whether the mixture used is rich or weak in gas; the rich mixture can be fired slowly and the weak one rapidly, just as may be required. The rate of ignition of the strongest possible mixture is so slow that the time of attaining complete inflammation depends on the amount of mechanical disturbance permitted.

According to Mr. Clerk, the following are the names of the first to propose each type:

			Year.
Type 1.	Explosion acting on piston connected to crank	W. L. Wright	1833
	,, ,, free piston	Barsanti & Matteucci	1857
Type 2.	Compression after ignition but at constant pressure	C. W. Siemens	1860
	Compression with increase in vol. .	F. Millon	1861
Type 3.	Compression with increase in pressure after ignition but at constant volume .	F. Millon	1861

From the considerations advanced, it will be seen that the cause of the comparative efficiency of the modern type of gas-engines over the old Lenoir and Hugon engine is to be summed up in one word, "compression." Without compression before ignition an engine cannot be produced giving power economically and with small bulk. The mixture used may be diluted, air may be introduced in front of gas and air, or an elaborate system of stratification may be adopted, but without compression no good effect will be produced.

The proportion of gas to air is the same in the modern gas engine as was formerly used in the Lenoir, the time taken to ignite the mixture is the same, the only difference is compression. The combustion, or rather the rate of inflammation, is indeed quicker in the modern engine because the volume of mixture used at each stroke is greater, and yet the time taken to completely inflame the mixture is no more than in the old type. The cause of the sustained pressure shown by the diagrams is not slow inflammation (or slow combustion as it has been called), but the dissociation of the products of combustion, and their gradual combination as the temperature falls, and combination becomes possible. This takes place in any gas engine, whether using a dilute mixture or not, whether using pressure before ignition or not, and indeed it takes place to a greater extent in a strong explosive mixture than in a weak one.

The modern gas engine does not use slow inflammation (or slow combustion if the term be preferred), but when working as it is intended to do, completely inflames its gaseous mixture under compression at the beginning of the stroke. By complete inflammation is meant complete spread of the flame throughout the mass, not complete burning or combustion. If by some fault in the engine or igniting arrangement the inflammation is a gradual one, then the maximum pressure is attained at the wrong end of the cylinder, and great loss of power results.

Compression is the great advance on the old system; the greater the compression before ignition the more rapid will be the transformation of heat into work by a given movement of the piston after ignition, and consequently the less will be the proportional loss of heat through the sides of the cylinder. The amount of compression is of course limited by the practical consideration of strength of the engine and leakage of the piston, but it is certain that compression will be carried advantageously to a much greater extent than at present. The greatest loss in the gas engine is that of heat through the sides of the cylinder, and this is not astonishing when the high temperature of the flame in the cylinder is considered. In larger engines using greater compression and greater expansion it will be much reduced. As an engine increases in size the volume of gaseous mixture used increases as the cube, while the surface exposed only increases as the square, so that the proportion of volume of gaseous mixture used to surface cooling is less the larger the engine becomes. Taking this into consideration it may be accepted as probable that an engine of about 50 indicated HP. could be made to work on 12 cubic feet of coal-gas per indicated HP. per hour, or a duty of about 32 per cent.

The gas-engine is as yet in its infancy, and many long years of work are necessary before it can rank with the steam engine in capacity for all manner of uses; but it can and will be made as manageable as the steam engine in by no means a remote future. The time will come when factories, railways, and ships will be driven by gas engines as efficient as any steam engine, and much more safe and economical of fuel. Gas generators will replace steam-boilers, and power will not be stored up in enormous reservoirs but generated from coal direct as required by the engine.

The data used by Mr. Clerk in his Paper on "The Theory of the Gas Engine," are

Specific heat of air at constant vol. .	=	0·169; water 1·00
„ „ „ pressure	=	0·238
Mechanical equivalent of heat foot-lbs. Centigrade	=	1389·6
Specific heat of air at constant vol. in foot-lbs. for 1 cubic foot at 17° C. and 760 m.m. barometer .		17·6 foot-lbs.
Specific heat of air at constant pressure in foot-lbs for 1 cubic foot from 17° C. and 760 m.m. . .		24·8 foot-lbs.
Weight of 1 cubic foot of air at 17° C. and 760 m.m. . .		0·075 lb.

Burning completely in oxygen, the following substances are taken as evolving the noted amounts of heat in Centigrade units, per unit weight of substance burned.

Hydrogen	34,170
Carbon	8,000
Carbonic oxide	2,400
Marsh-gas	13,080
Olefiant-gas	11,900

CHAPTER IX.

THE GAS ENGINE INDICATOR-DIAGRAM.

PROFESSORS W. E. AYRTON, F.R.S., and John Perry, M. E., have considered it necessary that help should be given to practical men to enable them to use such observations as they are constantly making, and to this end read a paper before the Physical Society of London, intended to teach such men a *method* of obtaining information from the indicator-diagram of a gas engine. The following is a condensation of the principal parts of this paper:—

The action in the Otto Gas Engine.—When the piston is at the end of its stroke, only what is called the clearance-space behind it is filled with fluid. This fluid is a mixture of carbonic acid, water-vapour, and nitrogen, whose temperature is about 410° C., if there was an immediately previous explosion. The temperature of the clearance space fluid may be anything between 410° C. and the temperature of the atmosphere, depending on how recently an explosion has taken place. As the piston moves forward it draws into the space a mixture of gas and air. At the end of the forward stroke the pressure of the mixed fluid is nearly that of the atmosphere; in the back stroke the fluid is compressed. At the beginning of the next forward stroke the fluid is ignited, and rapid development of heat results, causing great increase in pressure, the pressure gradually diminishing until, just before the end of the forward stroke, the fluid is allowed to escape. In the next back stroke the piston drives the fluid out of the cylinder with the exception of what remains in the clearance, and thus completes a cycle of operations. Indicator-diagrams show the nature of the alterations in pressure and volume going on during the compression and working parts of the cycle; distances measured as abscissæ representing pressure in pounds per square inch from vacuum, and distances measured as ordinates representing volume of the fluid, the unit of volume being the volume described by the piston moving through one foot of the length of the cylinder.

The shape of the diagram is materially modified by the recentness of the last explosion, as this effects the temperature of the fluid before compression, and so modifies the actual amount of the mixture of gas and air entering the cylinder. To a less degree the shape of the diagram is affected in the discharge part of the cycle by the recentness of an explosion, as a recent explosion will have given the exhaust passages a higher temperature.

The Nature of the Working Fluid.—For the purpose of showing the nature of the working fluid Table I. was constructed by Professors Ayrton and Perry. It will be seen from this that a mixture of 6·760 cubic feet of air and coal-gas becomes, after complete combustion, 6·4977 cubic feet of carbonic acid, water-vapour, and nitrogen, reduced to the same pressure and temperature without condensation of the water-vapour. Now as there is always an excess of air, and as the mixture before combustion has added to it nearly six cubic feet of the products of previous combustions, we have something like 13·3 cubic feet before combustion becoming 13·0377 cubic feet after combustion, at equivalent pressure and temperatures. The contraction is only about 2 per cent. We therefore may regard the fluid in a gas-engine as a fluid which, however it may receive heat, obeys approximately the characteristic law,

$$\frac{pv}{T} \text{ constant}$$

(where p is pressure, v volume, and T the absolute temperature), in so far as mechanical actions are concerned. That is, we may speak of it as a perfect gas, which receives heat from without, neglecting the fact that it is its own molecular energy which appears as heat. It is also approximately true that the ratio of the specific heats of the fluid is unchanged by combustion taking place.

In Table II. is given a similar comparison for Dowson gas:—

2·1325 cubic feet of combustible mixture become 1·9143 cubic feet;

or, taking into account the clearance-space and its products of past combustions, we have, say,

TABLE I.—COAL-GAS.

	Hydrogen, H_2.	Carbonic oxide, CO.	Marsh-gas, CH_4	Olefiant gas, C_2H_4.	Tetrylene, C_4H_8.	Nitrogen, N.	Carbonic acid, CO_2.	Water-vapour, H_2O.	Total.
Cub. ft. in 1 cub. ft. of gas	0·4600	0·0750	0·3950	0·0253	0·0127	0·0050	0	0·0200	
Heat evolved per cubic foot of each	191·12	190·02	592·6	932·	1702	0	0	0	
Heat evolved by given amount of each	87·92	14·25	234·1	23·58	21·61	0	0	0	381·46 or 530,230 foot-pounds.
Oxygen required by one cubic foot of each ...	0·5	0·5	2	3	6	0	0	0	
Product of combustion per cubic foot of each	1·0	1·0	3	4	8	0	0	0	
Oxygen required by given amount of each	0·2300	0·0375	0·790	0·0759	0·0762	0	0	0	1·2096 cub. ft. of oxygen per cub. ft. gas, or 5·760 cub. ft. of air per cub. ft. of gas.
Volume of product of combustion	0·460	0·075	1·1850	0·1012	0·1016	0·005	0	0·020	1·9478 + 4·5499 of nitrogen or 6·4977

TABLE II.—DOWSON GAS.

	Hydrogen, H_2.	Carbonic oxide, CO.	Marsh-gas, CH_4.	Olefiant gas, C_2H_4.	Tetrylene, C_4H_8.	Non-combustible.	Total.
Cub. ft. in 1 cub. ft. of gas	0·1873	0·2507	0·0031	0·0020	0·0011	0·5555	
Heat evolved per cubic foot of each	191·12	190·02	592·6	932·05	1702	0	
Heat evolved by given amount of each	35·79	47·63	1·837	1·864	1·872	0	88·99, or 123696·1 foot-pounds.
Oxygen required by given amount of each	0·0936	0·1254	0·0062	0·0060	0·0066	0	0·2378 cubic feet of oxygen per cubic foot of gas, or 1·1325 cubic feet of air per cubic foot of gas.
Volume of product of combustion	0·1873	0·2507	0·0093	0·0080	0·0088	0	·4641 + ·4898 of N in gas + ·0657 of CO_2 in gas + ·8947 of N in air introduced = 1·9143.

4 cubic feet becoming 3·7818 cubic feet; or contracting by nearly 5½ per cent. of its volume.

In Tables III. and IV. are calculated the specific heat of a mixture of 1 cubic foot of coal-gas, 5·76 cubic feet of air, and 4·5 cubic feet of products of a previous combustion, before and after combustion takes place. The Centigrade scale of temperature is employed.

TABLE III.—COAL-GAS BEFORE COMBUSTION.

Constituent.	Amount in fluid.	Specific heat at const. pressure per unit volume.	Specific heat at constant volume per unit volume.		
	Cubic feet. q.	C_p.	C_v.	qC_p.	qC_v.
Hydrogen.........	0·46	·2359	·99 × ·168	·1085	·4554 × ·168
Carbon monoxide	0·075	·237	1 ,,	·0178	·0750 ,,
Marsh-gas	0·3950	·3277	1·54 ,,	·1294	·6082 ,,
Olefiant gas......	0·0380	·4106	2·03 ,,	·0156	·0771 ,,
Nitrogen	0·0050	·237	1 ,,	·0012	·0050 ,,
Water-vapour ...	0·0200	·2984	1·36 ,,	·0060	·0272 ,,
Air	5·76	·2374	1 ,,	1·3680	5·760 ,,
Products	4·5	·2581	1·124 ,,	1·1614	5·058 ,,
Total	11.253	...	......	2·8079	12·066 × ·168 or 2·027
Or $C_p = 0.2496$, $C_v = 0·1802$. Ratio ...... 1·385					

In Tables V. and VI. similar calculations are made for the usual mixture of Dowson gas with air and products of previous combustion.

The specific heats given are those of the constituents in the cold state. Seeing, however, that there is no

TABLE IV.—COAL-GAS AFTER COMBUSTION.

	Cubic feet. *q*.	C_p.	C_v.	qC_p.	qC_v.
Water-vapour ...	1·3714	·2984	1·36 × ·168	·4092	1·865 × ·168
Carbon dioxide...	0·5714	·3307	1·55 ,,	·1889	·8855 ,,
Nitrogen	4·5554	·2370	1 ,,	1·0790	4·5554 ,,
Total	...	...	......	1·6771	7·3059 × ·168 or 1·227

Or C_p=0·2581, C_v=0·1889. Ratio ...... 1·367

TABLE V.—DOWSON GAS BEFORE COMBUSTION.

	Cubic feet. *q*.	C_p.	C_v.	qC_p.	qC_v.
Hydrogen.........	·1873	·2359	·99 × ·168	·0442	·1854 × ·168
Carbon monoxide	·2507	·237	1 ,,	·0594	·2507 ,,
Marsh-gas	·0031	·3277	1·54 ,,	·0010	·0048 ,,
Olefiant gas......	·0031	·4106	2·03 ,,	·0013	·0063 ,,
Nitrogen	·4898	·237	1 ,,	·1161	·4898 ,,
Carbon dioxide...	·0657	·3307	1·55 ,,	·0217	·1018 ,,
Air	1·1325	·2374	1 ,,	·2689	1·1325 ,,
Products	2	·2594	1·1323,,	·5188	2·2646 ,,
Total	4·1322	...	......	1·0314	4·4359 × ·168
				·2496	1·0735 × ·168 or ·1803

Ratio .... 1·385

TABLE VI.—DOWSON GAS AFTER COMBUSTION.

	q.	C_p.	C_v.	qC_p.	qC_v.
Water-vapour ...	0·2019	·2984	1·36 × ·168	·0602	·2746 × ·168
Carbon-dioxide...	0·3279	·3307	1·55 ,,	·1084	·5083 ,,
Nitrogen	1·3845	·2370	1 ,,	·3281	1·3845 ,,
				·4967	·21674 ,,
Total	1·9143	...	......	·2594	1·1323 × ·168 or ·1902

Ratio .... 1·3637

great change due to combustion, we may for many practical purposes assume that the specific heats remain the same at all temperatures. We have less right when using Dowson gas than when using coal-gas to make our assumption, which is that the fluid in the gas engine, from the beginning of its compression until it is allowed to escape, behaves like a perfect gas, receiving heat from an outside source.

Study of the Shapes of the Compression and Expansion parts of the Diagram.—The first problem which comes before us is the determination of the shape of the indicator diagram. It will be generally observed that, although the ignition parts of the various diagrams differ greatly, on account of differences in *the amounts of gas supplied,* the curves agree in their compression and expansion parts. If the clearance-space is occupied by fluid when the piston is fully at the end of its stroke; and if λ is the distance in feet passed through by the piston from the end of its stroke, the stroke being $1\frac{1}{3}$ foot, the clearance is $0{\cdot}889$ foot, and $\gamma+0{\cdot}889$, or l feet expresses the volume of the fluid at any instant. Measurements of l and p were made by the Professors for the particular engine under indication by them on the expansion-curves of the indicator-diagrams, and tabulated with $\log l$ and $\log p$.

If the law of the expansion-curve be assumed

$$pl^m \text{ constant,}$$

we have $\log p+m \log l=k$; so that when we plot log

p and log l on squared paper as coordinates of points, these points ought to lie in a straight line if our assumption is correct. Taking the straight line which lies most evenly among them, the professors found it defined by

$$\log l = 0\cdot313, \text{ when } \log p = 1\cdot7,$$
$$\log l = 0\cdot0425, \text{ when } \log p = 2\cdot1.$$

Hence

$$1\cdot7 + 0\cdot313\ m = k,$$
$$2\cdot1 + 0\cdot0425\, m = k.$$

Hence

$$m = 1\cdot479 \text{ and } k = 2\cdot1629.$$

Now

$$\log 145\cdot5 = 2\cdot1629.$$

Hence the law of expansion is

$$pl^{1\cdot479} = 145\cdot5. \quad . \quad . \quad . \quad (1)$$

In the same way the law of the compression curve is

$$pl^{1\cdot304} = 39\cdot36. \quad . \quad . \quad . \quad (2)$$

It is obvious that the expansion-curve (1) is steeper than the adiabatic, if we assume that the ratio of specific heats of the fluid is 1·37, as the equation of the adiabatic curve is

$$pl^{1\cdot37} = \text{constant}.$$

Again, the compression curve (2) has less slope than the adiabatic.

Influence of Vibrations of the Indicator-spring.—The Professors point out that it is exceedingly necessary, in obtaining the law of expansion, to take many points in the curve, and, either by using the alegbraic method or by the use of squared paper, to determine the most probable value of the constants. Engineers are constantly in the habit of determining these constants from measurements of the coordinates of two points only in the curve, forgetting that the position of either point may be much influenced by the vibrations of the indicator. The sinuous shape of the expansion-curve is specially noticeable in the early part of the expansion-curves of gas engine diagrams.

The Professors also say, "It is further to be remarked that the vibration of the indicator spring is very visible in the expansion part, because we have every reason to believe that the expansion part ought to have no sinuosities; but it is our belief that this vibration has its effect on the explosion part of the curve as well, and that it is of the utmost importance to find some means of eliminating the effects produced by these vibrations of the indicator-spring.

In our communication to the "Journal of the Society of Telegraph Engineers," p. 391, vol. v. (1876), we showed how to eliminate such vibrations in any case where the effect to be measured followed a regular law of increase or diminution, as in the case of the expansion part of this indicator-diagram. We have not yet sufficient information to enable us to employ this method on the explosion part.

The rule which we arrived at is as follows:—Draw two curves, A and B, through the highest and lowest points of the wavy curve which represents the actual observations: draw ordinates; the points of bisection of the parts of the ordinates intercepted between A and B lie on the correct curve.

Empirical Formula for the whole Diagram.—Now, inasmuch as the compression and expansion parts of all the curves follow the same laws, it would seem to be important to obtain one general formula for all the diagrams with one or more variable parameters. It is found that when we produce the expansion-curve (using formula 1), and when we divide the pressure QR at any part of the stroke by the corresponding ordinate LR of the expansion curve, doing this for many parts of the stroke, we get the ordinates of curves, which are nearly formed of straight lines, from the study of which it is found that the ignition and expansion parts of any diagram satisfy approximately the law

$$p = 145{\cdot}5 \, l^{1{\cdot}479}\{\kappa' + n\lambda - \sqrt{(\kappa - n\lambda)^2 + s}\} \quad (3)$$

The smaller the value of s the more nearly do the curves approach straight lines. These constants are evidently easily calculated from any diagrams.

The recentness of the last explosion affects the temperature of the mixture of gas and air, and therefore the mass of the mixture. Hence the expansion parts of successive indicator-diagrams often do not coincide. The law

$$p = \mathrm{M} \, l^{-1{\cdot}479} \{\kappa' + n\lambda - \sqrt{(\kappa - n\lambda)^2 + s}\},$$

where κ', κ, and n are constants, satisfies all the diagrams.

n is a constant whose value depends on the point in the stroke at which the maximum pressure occurs; and this, for a given speed of engine, depends principally on the proportion of gas to air in the mixture;

M is a constant which depends on the recentness of the last explosion.

Simple Formulæ for the Ignition and Expansion Parts of the Diagram.—The complete formula (3) assumes no want of continuity in proceeding from the ignition to the expansion part of the diagram. For the sake of ease in practical calculations we may, however, assume that the ignition and expansion-curves are quite discontinuous, employing some method of indicating continuity when results are plotted on squared paper. We assume that the lines are quite straight, so that—

The ignition part of curve is $(a + b\lambda)\ \kappa l^{-m}$, (4)
The expansion part of curve is κl^{-m}. . . (5)

To use formula (4) in any given case. Find by the method already given, the constants of equation (5) to the expansion part. Assume that the ignition is complete when $\lambda = \lambda_1$. Let the pressure at the beginning of the stroke be p_0; calculate the value of κl^{-m} when $\lambda = 0$, that is, when $l =$ clearance or l_0, say; then

$$p_0 \div \kappa l_0^{-m} \text{ is } a,$$

and

$$a + b\lambda_1 = 1;$$

so that

$$b = \frac{1 - a}{\lambda_1},$$

or

$$a = \frac{p_0}{\kappa} l_0^m \text{ and } b = \frac{1 - \frac{p_0}{\kappa} l_0^m}{\lambda_1}$$

The rate at which the Fluid receives Heat as calculated from its Volume and Pressure.—We* shall now proceed to calculate the heat received by the fluid. This we shall do as if, instead of there being combustion going on among the particles of the fluid, we had the fluid a perfect gas receiving heat from a great number of little furnaces, or pieces of hot wire immersed in the fluid. Besides the heat here considered, we have the heat radiated to the cold cylinder.

If A is the area of the piston in square inches, p the pressure of the fluid in pounds per square inch, and l the distance moved through by piston in feet, the work done by the fluid on the piston in an element of length dl is

$$Ap\, dl \text{ foot-pounds.}$$

It is evident that if we represent the heat which is received by the fluid in the length dl by

$$Aq\, dl \text{ foot-pounds,}$$

we may regard q as the rate (per foot-travel of the piston) at which heat is received by the fluid, just in the same sense as p the pressure is the rate at which work is done by the fluid; and a comparison of q and p shows at once the comparison between the rates at which heat is being received and work is being done.

---

* It is to be understood that these are the words of Professors Ayrton and Perry.

Now, since we consider the fluid to behave like a perfect gas, we know from thermodynamics that

$$q = \frac{1}{\gamma - 1}\left(\gamma p + l\frac{dp}{dl}\right), \quad . \quad . \quad (6)$$

where $\gamma = 1·37$; and it is obvious that the relation of p to q is not altered in any way by altering the scale to which l or p is represented in the indicator-diagram.

As we know that the expansion part follows a law

$$p = \kappa l^{-m},$$

it is obvious that

$$q = \frac{\gamma - m}{\gamma - 1} p,$$

being proportional to the pressure. There is great importance in obtaining a formula such as that given for the shape of the indicator-diagram.

Total Heat and Work of One Cycle.—The integral of $q.dl$ multiplied by the area A of the piston in square inches gives the total heat received by the fluid during any part of the stroke, and is evidently

$$\mathrm{A}\int_{l_1}^{l_2} q\,.\,dl = \frac{\mathrm{A}}{\gamma - 1}\,(p_2 l_2 - p_1 l_1) + \mathrm{A}\int_{l_1}^{l_2} p\,.\,dl.$$

As we know that combustion, about the period of opening of the exhaust-valve, is just sufficient to supply the loss by radiation to the cylinder without having much effect on the volume and pressure of the fluid, we can assume that any combustion after that time produces heat which is radiated to the cylinder. We are told that there is no combustion in the exhaust. For the small amount of combustion after the exhaust-valve opens we do not see our way at present to the basis of any but the very roughest assumption, and we think that attention ought to be paid to this matter in future investigations. What complicates the question is the fact that the mass of the fluid which radiates heat to the cylinder rapidly gets less after the exhaust-valve opens. To obtain a first approximation, we may assume that the heat of combustion after the exhaust-valve opens is equal to the work done in the forward stroke after that time.

The heat retained by the fluid is 1·94 W.

The gases in the exhaust-pipe close to the cylinder are known to have a temperature not much greater than 400° C. Hitherto it has been customary to calculate the amount of heat carried off by the gases through the exhaust-pipe from the heat-capacity multiplied by the difference of temperature from that of the atmosphere. It must be remembered, however, that the total heat of combustion of coal-gas contains the latent heat of the steam produced, and that the exhaust gases carry off this heat. Hence the amount of about 0·95 W, deducible from the experiments of Messrs. Brooks and Steward, must be increased by two thirds of itself, giving 1·57 W as the energy carried off by the gases in the exhaust-pipe, where W is the work of a cycle.

Hence (1·94−1·57) W_1 or 0·37 W, is the amount of energy which is lost by the fluid from the opening of the exhaust-valve until the fluid is passing along the exhaust-pipe outside the cylinder. This is largely expended in heating the cylinder itself, in friction at bends in the exhaust-valve, &c.; so that it disappears as radiated heat, and as heat given to the water-jacket during the remaining parts of the cycle. Now, we may safely take it that the expenditure of gas is about 22 cubic feet per hour per indicated horse-power; so that, using the heat of combustion calculated in Table I., the total energy of combustion of the gas used is 5·91 W; and we are now in a position to make the following table. Of the 5·91 W, the total energy of combustion of a charge, we have for a particular case, say:

1·38 W. Work of forward working-stroke till exhaust-valve opens.
0·14 W. Work of forward working-stroke after exhaust-valve opens.
2·31 W. Heat given to the cylinder during forward working-stroke by radiation before exhaust-valve opens.
0·14 W. Heat of combustion after exhaust-valve opens and which is radiated to the cylinder.
1·57 W. Heat carried off by gases in exhaust-pipe.
0·37 W. Given to the cylinder as heat after the exhaust-valve opens, partly by friction at the exhaust-valve, partly during the succeeding three-fourths or non-working parts of the cycle.

It is found by experiment that the water from the water-jacket carries off somewhat more than 50 per cent. of the total heat of combustion, or 2·96 W; but it is almost impossible to make this measurement accurately for one cycle. It is sometimes as much as 62 per cent. and sometimes as little as 35 per cent. Again, the cylinder loses heat by radiation as well as by the water-jacket; so that, even if we could assume that such a number as 50 per cent. is correct, we are still not in a position to state the total loss of heat from the cylinder.

It is to be remembered that W is the indicated work. The useful work of a gas-engine, given out by the crank-shaft, is about 0·8 W, there being an expenditure of 0·2 W in overcoming the mechanical friction of the engine.

Rate at which Fluid radiates Heat to cold Cylinder.—It was found by the pyrometric measurements of Messrs. Brooks and Steward that the temperature of the products of combustion in the clearance-space, if there has been a recent explosion, is about 410° C.; and for the purpose of determining the temperature of the fluid before compression, they take 1·4 volume of coal-gas and 9·25 of air at 22° C. with 7·94 volumes of products of past combustions at 410° C., from which, assuming that the specific heats of the constituents do not alter with temperature, they find that the temperature of the mixture before compression is 120° C. This is sufficiently correct and with the data given in their paper quoted p. 74, there should be no difficulty in the proper understanding of a gas engine indicator diagram.

EN

PLATE Nº 1. FIGS. 1 TO 6.

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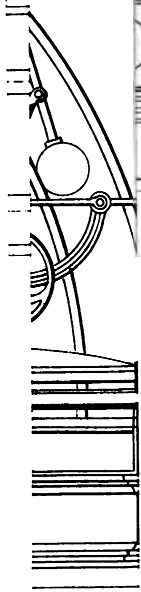

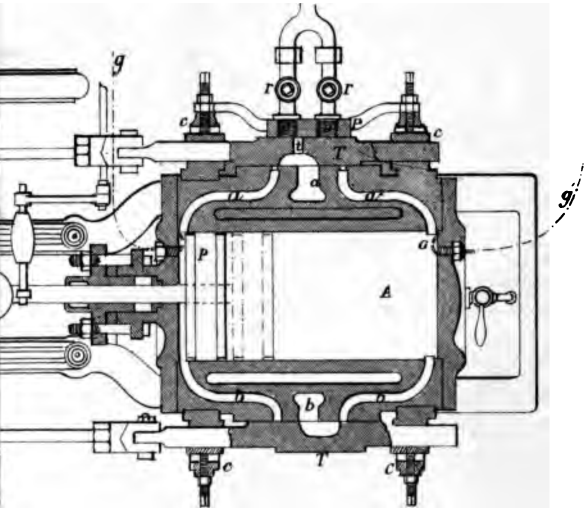

FIG. 6.

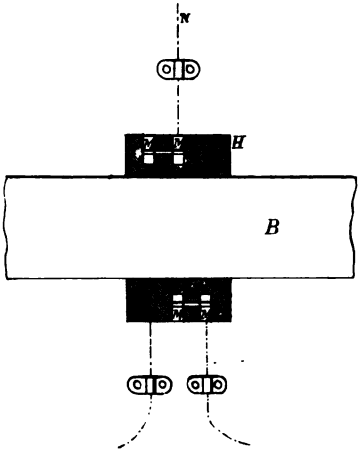

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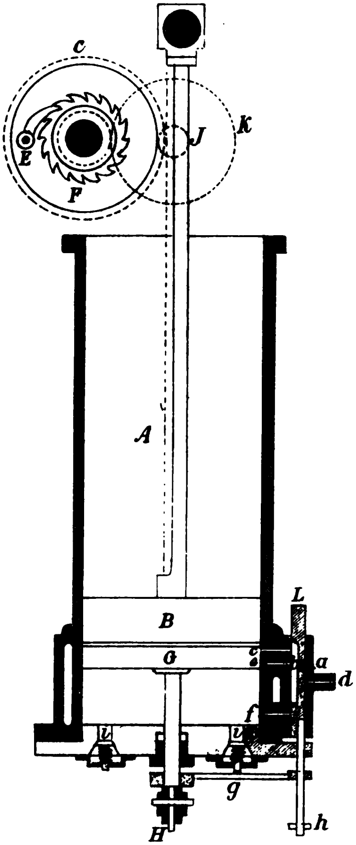
PLATE No. 2. FIGS. 7 TO 15.

FIG. 14.



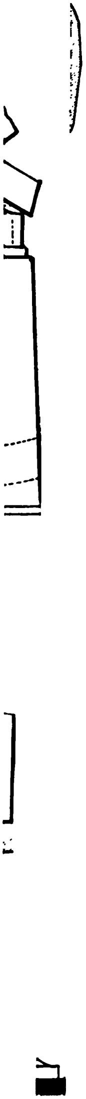


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PLATE No. 1. FIGS. 1 TO 6.

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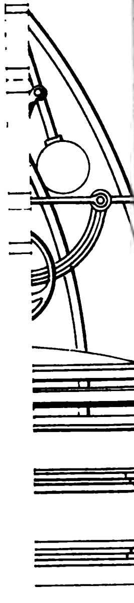

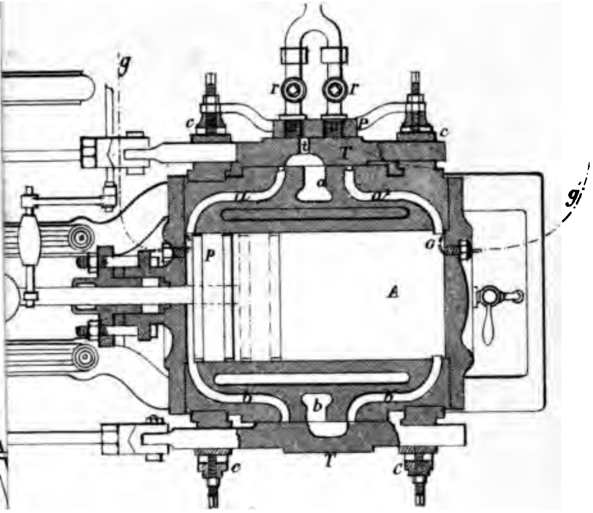

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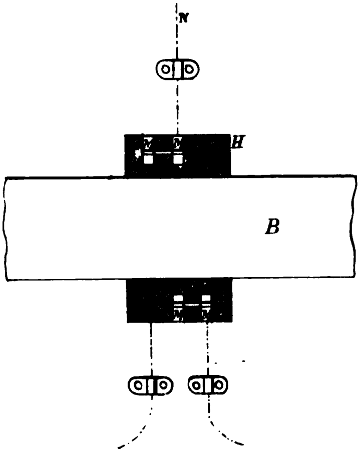

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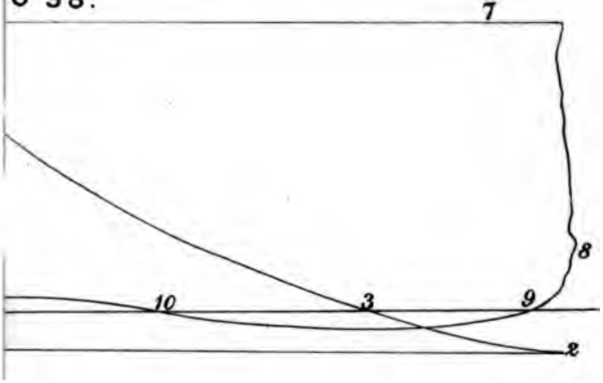
PLATE Nº 4. FIGS. 27 TO 41.

C 38.



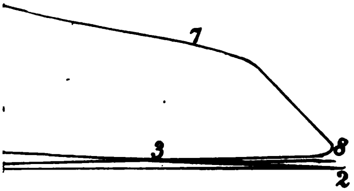


FIG 39

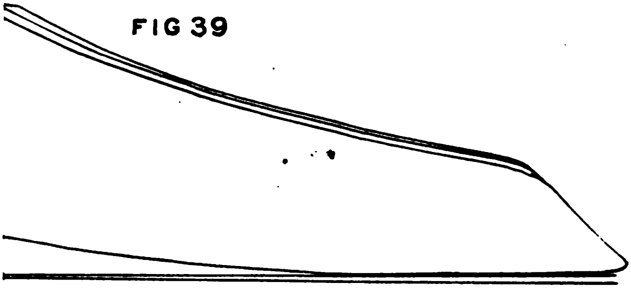


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PLATE No. 2. FIGS. 7 TO 15.

FIG. 14.

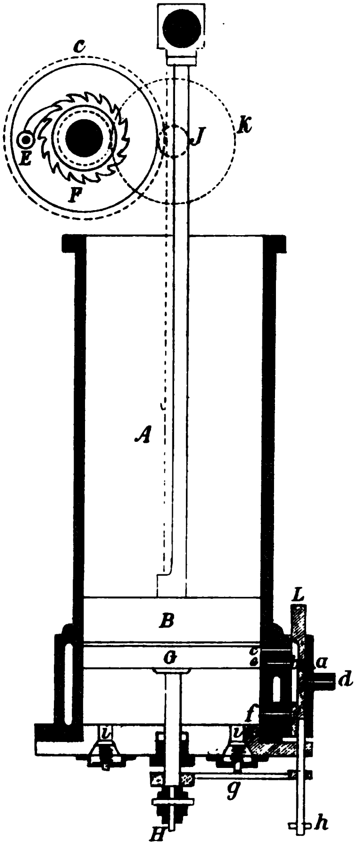
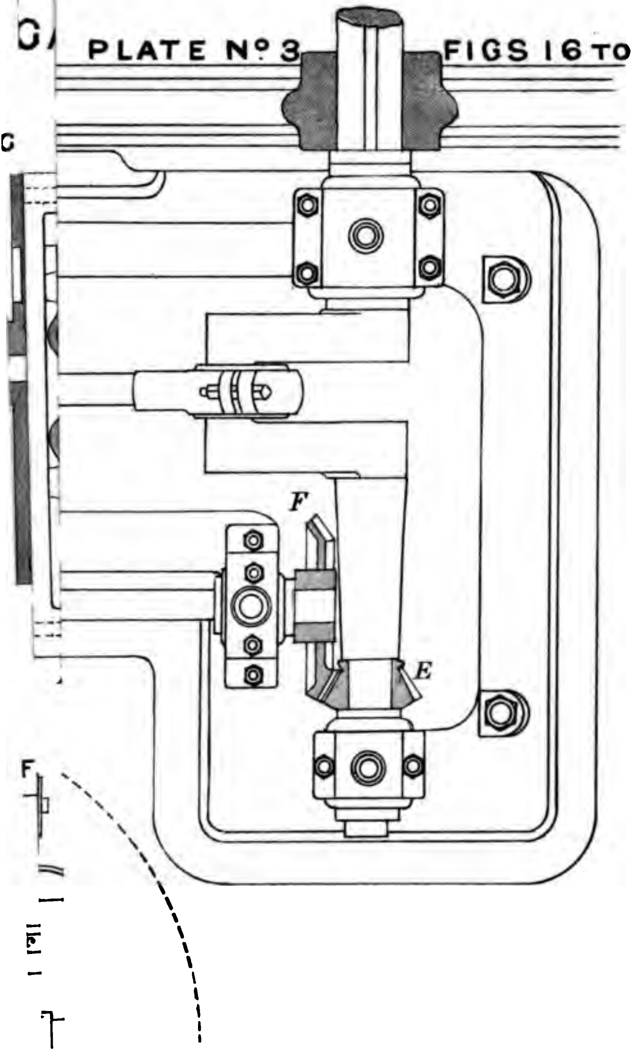


PLATE Nº 3 FIGS 16 TO 26.



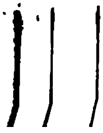


PLATE Nº 4. FIGS. 27 TO 41.

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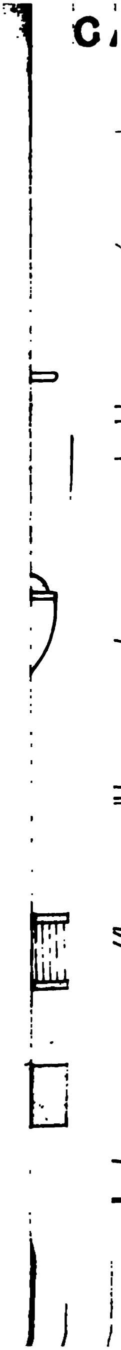

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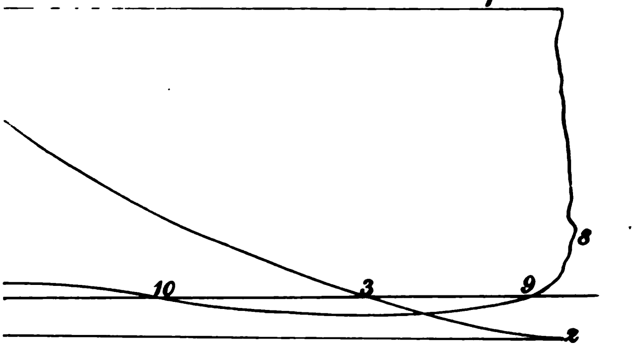

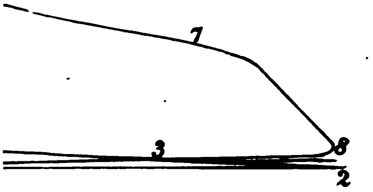

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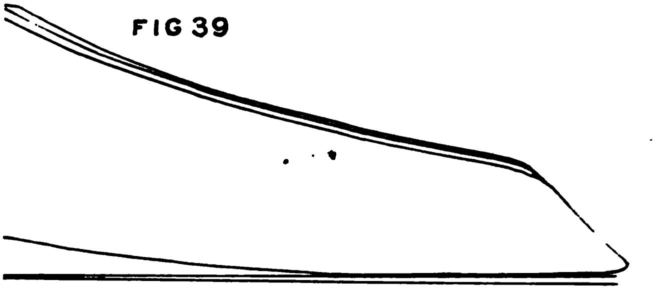

PLATE Nº 4. FIGS. 27 TO 41.

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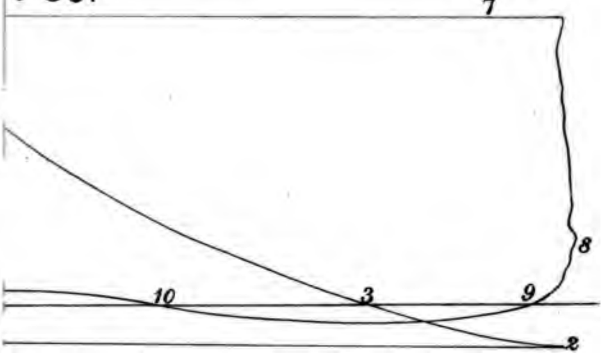

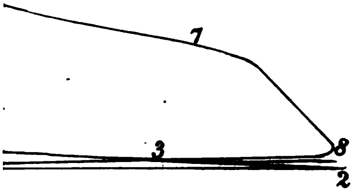

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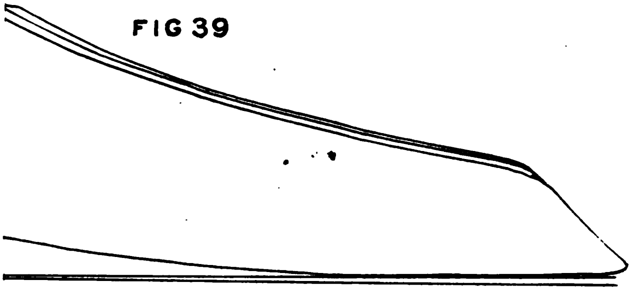


PLATE Nº 5. FIGS. 42 to 48.

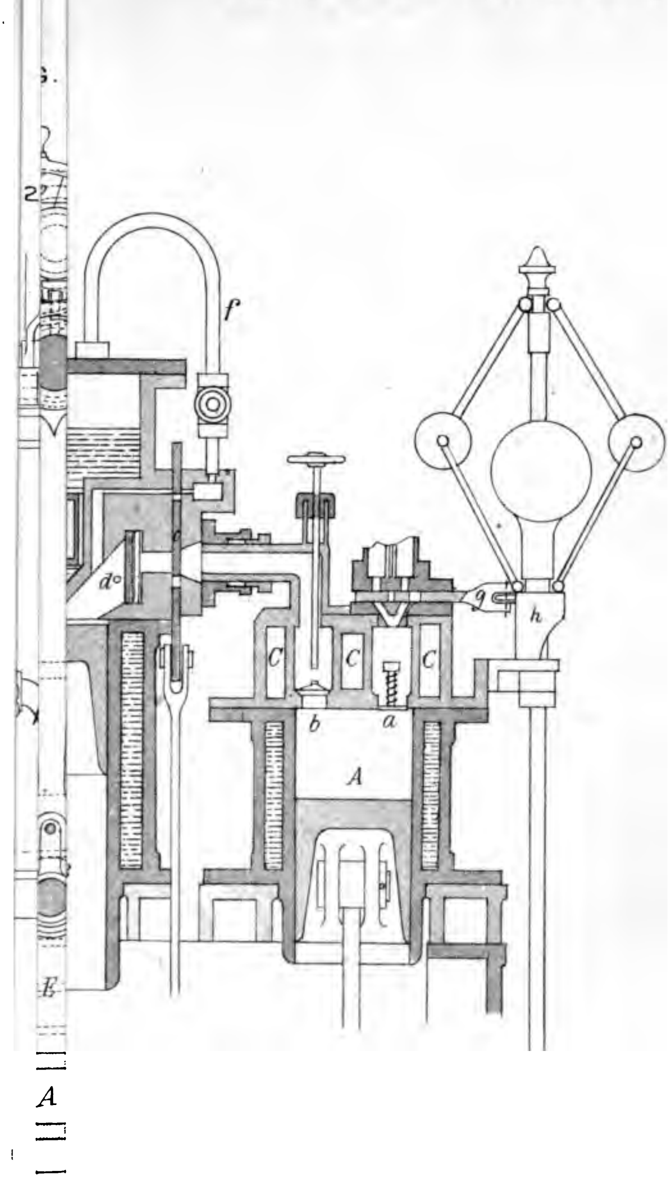
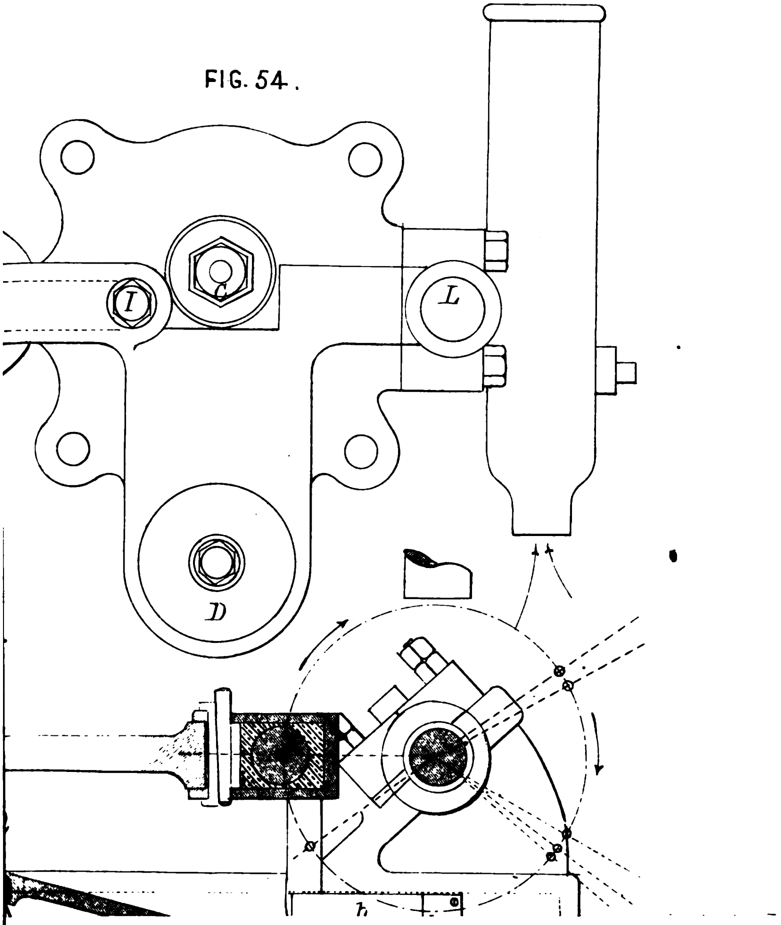
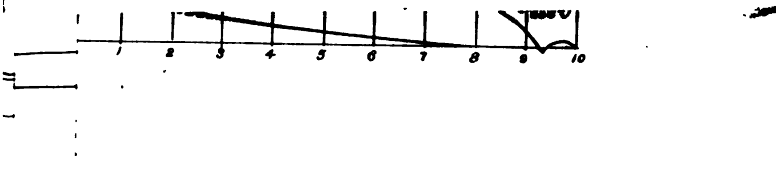


PLATE No 6. FIGS. 49 to 54.

FIG. 54.





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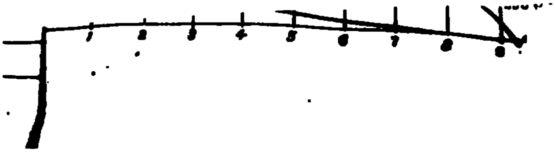

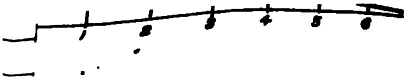

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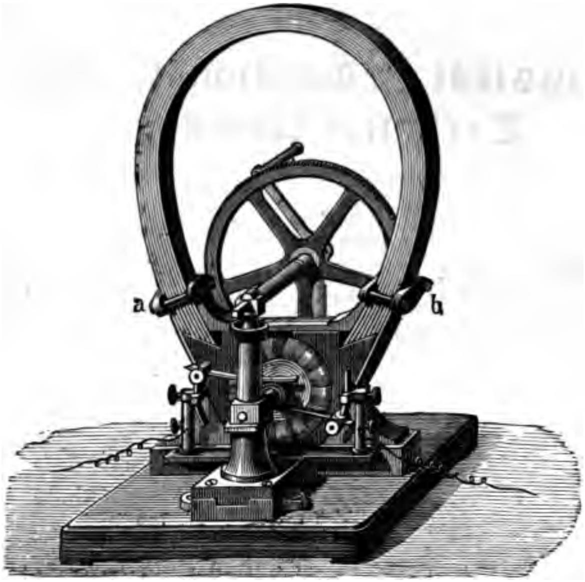

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